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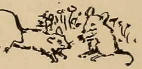

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BY

THOMAS C. CHAMBERLIN AND ROLLIN D. SALISBURY
Heads of the Departments of Geology and Geography, University of Chicago
Members of the United States Geological Survey
Editors of the Journal of Geology

IN THREE VOLUMES

VOL. II. EARTH HISTORY

GENESIS—PALEOZOIC

SECOND EDITION, REVISED

Vertebrate Paleontology
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PREFACE TO VOLUMES II AND III.

THE salient features of the purpose and plan of this work were set forth in the preface to Volume I, published two years ago. The subject of that volume, Geological Processes and their Results, is sufficiently distinct from the theme of these volumes, The History of the Earth, to give occasion for additional prefatory remarks. Though the subjects are thus measurably distinct, they have been given a common bond by the treatment of the geological processes in a historical way, on the one side, and by the development of the earth history on dynamical lines, on the other. Not only has the history been treated from a causal point of view in these volumes, but processes and principles have been discussed wherever the phase of the history has seemed to make such discussion particularly pertinent. Such special discussions have usually been introduced at the first stage in the history at which the phenomena they are intended to elucidate were declared features, or at which their expression is well suited to treatment. Sometimes, however, they have been delayed, to avoid emphasizing too many dynamic subjects at a given stage. Sometimes, too, the dynamic treatment has been divided between successive historical expressions, as when the subject is very complex, or when different phases are best expressed at different historical stages. This is the case, for example, with the dynamics of deformation, which were treated at some length in Volume I, are further discussed in the chapters on the origin and the early stages of the earth, are again touched upon in connection with several periods when deformation was pronounced, and are reverted to finally in the last chapter, in their application to the peculiar phenomena of the continental borders. A similar method is used in the treatment of climatic problems, particularly that of glaciation, which is considered at some length in connection with the remarkable Permian phenomena, because of its advantageous historical setting between antecedent and subsequent mild periods, and is resumed in connection with the recent glacial period, where localization and periodicity, together with many details, are best expressed. This recurrent treatment is intended to relieve, in some measure, the stress of treatment of these intricate themes at any one point, but more especially to combine dynamical discussion with the phenomena which it is to explain, as these phenomena unfold themselves stage by stage. This has been done in the belief that such discussions often have their most obvious force only in such relations, and in the further belief that the definite development of a historical problem in its natural associations is an advantageous antecedent to the discussion of the dynamic agencies that constitute its elucidation. It has been thought that this association of phenomena with their causes is important enough to justify even some reiteration of causes or relations, when these are essential to firm basal conceptions.

In harmony with this recurrent recognition of the dynamical element in the physical evolution of the earth, special effort has been made to give to the evolution of the successive phases of the earth's inhabitants their appropriate dynamic and physiographic relationships. In addition to the more familiar relations of life to its environment, the special function of the epicontinental seas and their oscillations has received emphasis, because these have been the chief media through which the more legible part of the geologic record has been made. As a corollary of this, the expansions and contractions of the land, on the one hand, and of the epicontinental seas, on the other, and their contrasted influences on the life of the land and of the shallow seas, respectively, have been given unusual prominence.

Special emphasis is also laid on the features of the ancient lands wherever the data permit. The sources of the sediments, and the modes and conditions of their derivation, at all stages, are regarded as equally important with the sediments themselves, and often more significant of vital conditions. Base-level states, on the one hand, and states of much relief, on the other, are recognized as influential factors in determining not only the character of the deposits, but the evolution of life on both land and sea. Terrestrial deposits, as distinguished from marine deposits, are recognized in many periods, particularly in the Devonian, Carboniferous, Permian, Triassic, Comanchean, and Tertiary, and in the last, notably in the Lafayette. The terrestrial deposits so recognized are not merely lacustrine, or even fluvial, in the narrower sense, but embrace also the products of general aggradation on surfaces of low gradient, by pluvial and other subaërial agencies.

On the physical side, the chief effort has been to give a connected and interpretative sketch of the earth's history, especially as exemplified by the North American continent. Imperfection of knowledge makes this sketch incomplete at some points, and limitations of space have made it brief, even when knowledge is more adequate. Both imperfection of knowledge and limitations of space have made it impracticable to deal with other continents as fully as with our own. It is believed, however, that the principles set forth in connection with the history of our own continent are applicable to all continents, and that the course of events in all has been, in principle and in leading facts, similar to that in our own.

While recognizing the alternative views, the doctrine of the permanence of the continents plays an unusually large part in the interpretations of continental evolution, of the migrations of life, and of the successive developments of provincial and cosmopolitan faunas. So also the doctrine of the periodicity of the great deformative movements forms a notable feature in the interpretations of life evolution, and in the reciprocal developments of land and sea life, as well as of provincial and cosmopolitan faunas.

Exceptional attention is given to the evolutions of faunas and floras and to their radiations and migrations, while less attention is given to the unrelated features of the life, however bizarre these may be in themselves. The familiar calling of the biological roll under each period is abandoned, and will perhaps be missed; but it has been thought that the mutations of the assemblages of composite life of the great provinces that arose in succession from changes in geographic configuration, are more important as elements in the history of the earth's inhabitants than the classification of life forms as such, particularly as such classification is still in a state of transition. The order of treatment of the various forms of life in the several periods is varied according to what is conceived to be their historical importance or natural relations.

Without giving special adhesion to any particular doctrine of life development, beyond a cordial recognition of the new mutation theory of DeVries, as well as the older and more familiar ones, the progressive evolution of life is made a subject of constant remark, with suggestions as to biological, as well as physiographic, relationship and dependence.

In the biological, as in the physical parts, the unsolved problems are frankly recognized, and the student is made a party to a common desire, if not a common effort, to secure more light on dark subjects. These volumes therefore attempt not merely to record the salient facts of historical geology, and to suggest dynamic relations and interpretations, but to indicate to rising geologists the need of further investigations, of more light, and of revised interpretations on not a few phases of the earth's history.

Perhaps the most radical departure of this work from the precedents of its class lies in the larger emphasis laid on the hypotheses of the origin of the earth, and especially in the introduction of a new hypothesis of earth genesis, whose dynamic sequences depart widely from familiar lines. This recognition of divergent hypotheses at the very outset necessarily involves an effort to carry through the interpretations of the whole history parallel systems of doctrine built on the diverse hypotheses recognized. Especially is it incumbent to try to carry out the logical sequences of the new hypothesis in its application to the main problems that remain unsolved, particularly those of deformation, vulcanism, and atmospheric states. Introduced concurrently with the more familiar views, these newer modes of interpretation form an alternative system running through the whole work. It is believed that this will be at least stimulating, whether or not it shall prove to be a step toward the final system of interpretation, which future research alone will determine.

A few new elements of geologic classification which have not usually received more than partial recognition in standard works are herein given full recognition. In the class of time-divisions technically designated *Eras,* the *Proterozoic,* long since proposed by Irving, has been adopted, and made to cover about the ground included under the Algonkian of the U. S. Geological Survey. In other words, it is made to include the group of chiefly sedimentary or meta-sedimentary systems below the Cambrian and above the great terranes of chiefly igneous or meta-igneous origin, referred to the Archeozoic. The Lower Carboniferous, or Sub-carboniferous, is recognized as a distinct system under the name *Mississippian,* which has already received some currency in America. The Lower Cretaceous is also recognized as a separate system under the name *Comanchean.* The reasons for these departures from current classification are set forth in the text. Some suggestions of further modification of the current classification are made, but not adopted, and in connection with them the criteria of classification are set forth.

Some periods have received fuller treatment than others for special reasons, usually for the sake of treating new features with some amplitude when they first present themselves in forms advantageous for exposition. The Cambrian period, for example, affords the first unmutilated record of a great sedimentary fossil-bearing system, and hence receives an elaboration that becomes unnecessary with its successors. So the Devonian period furnishes the first impressive expression of provincial life-evolution on a large scale; the Carboniferous, the first declared plant evolution; the Permian, the first well-deciphered glaciation; the Pleistocene, the immediate preparation for the human period, and so the text of these periods has been swollen by these special themes.

As in the previous volume, the endeavor has been made to keep the discussion as free from technicalities as practicable, and to render the matter readable. Certain of the more complicated problems of internal and atmospheric dynamics render this well-nigh unattainable, as frankly confessed by the relegation of certain portions to small type. The description of the many complexities of the geographic distribution and of the composition of the various formations cannot be wholly freed from tediousness to the general reader; but they are so essentially serviceable for local and special studies, and even for a concrete general conception of the variety of concurrent geological processes, that their admission is regarded as indispensable.

The three volumes are designed to furnish the basis for a year's work in the last part of the college course, or in the early part of a graduate course. It may seem at first thought that the amount of matter is rather large for this, but the educational saw, that, in things historic, nineteen pages of flesh-and-blood are an easier assignment than nine pages of bare-bones, is believed to have an application to geologic history. By judicious selection of material to be presented and omitted, the volumes will be found useful for briefer courses, and by the use of the numerous references to the discussions of special treatises, they may be made the basis for much more extended courses than are commonly given in undergraduate work. They will, it is hoped, be of service as reference books where short courses only are given.

No attempt has been made to make these volumes a manual, and the details of the geology of individual regions will not be found in them, except as these details have been thought necessary to the interpretation of the general phases of the subject. For local details, State and National Survey reports, and other special monographs, must be consulted.

In the account of the geology of each period, the text is so arranged that the physical history of the continent may be followed through consecutively, without especial reference to the history of the life, and conversely, so that the history of life may be followed through as an independent, unified subject. This is an adaptation to the convenience of those institutions whose division of instructional labor permits a separation of the treatment of the physical from the biological phases of the subject.

Acknowledgments, in addition to those made in Volume I, are due to many colleagues who have rendered valuable aid in the preparation of these volumes. In the portions relating to invertebrate paleontology, the assistance of Dr. Stuart Weller has been so generous and unreserved that he has been scarcely less than a collaborator. Almost as much may be said of the assistance of Drs. S. W. Williston and E. C. Case in the portions relating to vertebrate paleontology, and of Drs. J. M. Coulter and H. C. Cowles in paleobotany. The selection of the invertebrate illustrations and the preparation of the annotated legends have been largely the work of Professor Weller, and many of the figures for these illustrations have been redrawn for this work under his supervision by Miss Mildred Marvin. He has also read both the manuscript and the proof. Dr. Williston has read the manuscript and proof of the portions relating to vertebrate life. In the cosmological portions, the collaboration of Dr. Forest R. Moulton has been of indispensable service. In certain mathematical problems, Dr. A. C. Lunn has given valuable advice, and Dr. Julius A. Stieglitz has done the same in connection with chemical subjects. The colored map of the American formations has been prepared by Professor Bailey Willis. The series of analytical maps of the several periods were compiled and drawn by Mr. C. E. Siebenthal under the supervision of the authors. Many of the figures in the text were drawn by Mr. G. A. Johnson. In other ways, much valued aid has been rendered by Professors E. B. Frost, A. A. Michelson, C. R. Barnes, J. P. Goode, H. G. Gale, and Messrs. Edson S. Bastin and Eugene W. Shaw. Various individual investigators, publishers, and surveys, preëminently the U. S. Geological Survey, have furnished material for illustrations. In general these contributions are acknowledged in the text.

The references to Volume I are to the second edition, in which the pagination numbers are higher than those of the first edition by a little more than one in twenty, as a rule.

University of Chicago, December, 1905.

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GEOLOGY

VOL. II

GEOLOGY

CHAPTER I.

THE ORIGIN OF THE EARTH.

The strata of the earth reveal its history with great fidelity for long periods previous to the present, but earlier than that the record becomes indistinct, and if we attempt to follow it back to the beginning, the indistinctness merges into extreme obscurity. The rocks at the base of the known sedimentary series are so greatly disrupted, crumpled, crushed, metamorphosed, and traversed by intrusions, that their history is deciphered with the greatest difficulty and no little uncertainty, while below these lies the inaccessible interior of the earth whose formation constituted a still earlier chapter in the history. The nature of this inaccessible mass can only be inferred from volcanic extrusions, the transmission of seismic tremors, the phenomena of gravity, the distribution of rigidity and of internal heat, the modes and processes of deformation, and other phenomena of a more or less dynamic kind. All these phenomena have their bearing on the problem of the earth's origin, but just what they imply cannot yet be interpreted without some measure of reasonable doubt.

Besides these internal phenomena, suggestions relative to the origin of the earth are to be found in its characteristics as a planet, and in its relations to the other members of the solar system. Suggestions are also to be found in certain features of the solar system which show that it had no haphazard origin. The birth of the system is beyond doubt revealed in its constitution and in its dynamics, if one could but read the record. But all these phenomena of external relations, as of the hidden interior, are difficult to interpret, and the meaning they carry cannot be read as we read the sedimentary record. We do read dynamical records. In the fall of rain we readily read the previous ascent of vapor, not so much by any material record as through a known system of atmospheric dynamics. We readily follow the growth of an oak back to its origin by reversing its organic processes. By three observations of the apparent positions of a new comet, the astronomer traces its path both backward and forward. In a somewhat similar way, the history of the earth will doubtless in time be traced to its beginning through its dynamical characters. It is quite certain that the earth and the solar system were organized in pursuance of a definite succession of progressive changes which are virtually recorded in the phenomena of the present stage. When a fuller and deeper insight into such phenomena is attained, the record will doubtless become quite readable, and the interpretation sure.

While awaiting this, we must be content with hypotheses. Since these are our only resource, there is need to form as clear conceptions as possible of those hypotheses that have been or may be entertained, and of their working qualities as applied to the problems of the earth. It is not less important to acquire at the same time a hospitable and intelligent preparedness to appreciate new light as it shall present itself.

Not a few of the doctrines of geology, when traced back to their ultimate terms, are found to hang on some hypothesis of the earth's initial stage, and to have no greater strength than that hypothesis. It is therefore important to scrutinize these basal hypotheses, to note critically the ways in which they enter into the interpretation of the earth's phenomena, and into the various geological doctrines, and to carry into the study of earth-history a never-failing sense of these hypothetical dependencies. This should serve as a wholesome guard against the acceptance of conclusions as substantiated, when they are in reality hypothetical in their ultimate dependence; especially should it guard against the *unconscious* acceptance of conclusions as though they were demonstrated, when in reality, traced a step or two backward, they may be found to be grounded solely on a hypothesis.

It is the glory of geology that it is a growing science. While it has an enormous mass of the firmest data, and its great conclusions rest on most substantial grounds and will never be radically changed by any developments in the future, it has, at the same time, many problems that are yet unsolved, many doctrines that are yet debatable, many depths that are yet unfathomed. At all points, therefore, it invites an investigative spirit: it courts an attitude of independent thought and of critical scrutiny. Especially is this true of the hypotheses of the origin and early states of the earth, to which we now turn.

HYPOTHESES OF THE EARTH'S ORIGIN.

It is the nearly unanimous conviction of astronomers that the solar system was evolved in *some* way from a nebula of *some* form. Until recent years, the majority of astronomers accepted the special theory of Laplace, presently to be sketched. So general has been this acceptance that the theory of Laplace has come to be known as "The Nebular Hypothesis," and when this phrase is used without qualification, this particular hypothesis is usually meant. The advance of inquiry, however, makes it necessary now to consider at least two other hypotheses, each of which postulates that the solar system arose from a nebula, but a nebula whose constitution and mode of evolution differed from that postulated by Laplace. In a broad sense, all these are nebular hypotheses. Each of them embraces sub-hypotheses or variations, but in their basal features they are distinct and form three definite classes.

I. **The gaseous hypothesis.**—In this, the parent nebula is assumed to have been formed of gas aggregated by gravity in accordance with the laws of gases, and to have been evolved into the present state by a gradual passage from the original system of gaseous dynamics into the present system of planetary dynamics. The type of the class is the Laplacian hypothesis.

II. **The meteoritic hypothesis.**—In this, the parent nebula is assumed to have been a swarm of meteorites, the individual members of which moved in diverse directions and suffered frequent collisions, attended by heat, light, and vaporization. The type is the conception worked out by G. H. Darwin, in which the swarm of meteorites is thought to have behaved essentially as a coarse gas, the evolution of the system being dynamically like that of a gaseous system: indeed, the initial meteoritic aggregation may have actually passed, at a later stage, into a gaseous one by the vaporization of the constituent meteorites.

III. **The planetesimal hypothesis.**—In this, the constituents may be molecules or small masses of any kind moving in orbits about a common center. They are not primarily controlled by collision and rebound as in the preceding cases, but by revolution about their common center of gravity or some central body, as are the planets to-day. In other words the constituents are infinitesimal planetoids or planetesimals. Under this hypothesis the dynamical system was essentially the same at the outset as it is now; the evolution has consisted in the aggregation of the planetesimals into planets and satellites. Dynamically considered, it differs more from the other two hypotheses than they do from one another, but it is liable to be confused with the second, from which, however, it departs fundamentally. These three hypotheses will be considered in detail.

I. The Laplacian or "Nebular" Hypothesis.[1]

During the last century the Laplacian hypothesis of the origin of the solar system was almost universally accepted by men of science, and geological theories respecting the early states of the earth and respecting many of its subsequent events were built upon it, and these views remain largely prevalent to-day.

The postulated nebula.—The Laplacian hypothesis assumes that the matter of the solar system was once in an extremely heated gaseous condition and formed a vast spheroid extending beyond the outermost planet and rotating in the same direction as the present system. How this condition of things arose was not definitely postulated by Laplace. It has since been referred to the collision of two large bodies, and to other agencies. The extreme tenuity of the gaseous spheroid thus postulated is to be noted, for computation makes its average density but a small fraction of a millionth of the density of our atmosphere at the surface of the earth, while its outer density was very much less.[2] The hypothesis assumes that this extreme degree of rarefaction was maintained by intense heat.

Formation of rings.—The hypothesis holds that the gradual loss of this heat by radiation must have resulted in contraction; and that this must have led to accelerated rotation. When the rotation reached a certain speed, the centrifugal acceleration at the equator of the spheroid would come to equal the centripetal acceleration of gravity. The equatorial portion would then no longer contract, while the remainder, having less rotational speed and continuing to shrink from further loss of heat, would draw away from it. The equatorial portion is commonly said inaccurately to be "thrown off." The hypothesis assumes that the equatorial matter so left behind would constitute a ring resembling the rings of Saturn; indeed, there is little doubt that the Saturnian rings suggested the theory. It further assumes that, as the cooling and contraction of the spheroid continued, additional rings to the number of the present planets were left behind.

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[1] A somewhat similar hypothesis was advanced earlier by the philosopher Kant and a cruder one still earlier by Thomas Wright. Swedenborg also made a suggestion in the same line. These earlier attempts, however, commanded little attention, and the wide acceptance which the hypothesis gained later was due mainly to the elegant elaboration given it by the mathematical genius of Laplace, and to the great influence of his name which it properly bears. The hypothesis is here sketched in the slightly modified forms usually held at present.

[2] Kelvin gives the average density of a gaseous nebula having a radius forty times that of the earth's orbit, as 1/570,000,000 of that of common air at the ordinary temperature of 10° C. (Pop. Lect. and Add. I, p. 419). F. R. Moulton finds the average density when the nebula extended to the orbit of Neptune, 1/240,000,000 of average

It has been objected that the matter left behind in this way would separate particle by particle, forming a kind of disk, and not a series of definite rings, since the centrifugal acceleration would come into equality with the centripetal gradually and at different times for each successive distance from the center. There could have been no appreciable cohesion to restrain the separation; on the contrary, the individual velocities of the molecules should have aided individual separation. But this is not the view taken by the hypothesis.

Formation of gaseous spheroids.—It is further assumed that as the rings cooled they parted at their weakest points and collected into spheroids which were still hot and gaseous like the original spheroid. These afterwards followed a similar course of evolution, detaching rings in most cases, which in turn parted and gathered into smaller spheroids.

The spheroids into which the first set of rings contracted are assumed to have at length condensed into the several planets, those of the secondary rings into the satellites, while the great central spheroid formed the sun.

The earth-moon ring.—In the case of our planet, it is held that the matter of the earth and moon together was originally separated from the solar spheroid as a common ring at a rather late stage in the evolution of rings, and that this ring coalesced into a hot gaseous spheroid which, in the course of its contraction, in turn detached a ring from its equator, and that this ring condensed into the moon.

air at the earth's surface (Tests of the Nebular Hypothesis, Astrophys. Jour., Vol. II, 1890, p. 114).

According to the original Laplacian hypothesis, the earth, after the separation of the moon-ring, was still a spheroid of hot gas which continued to cool and shrink until finally its main mass passed into a liquid and at length into its present state.

Darwin's modification.—George H. Darwin [1] has proposed a modification of the theory, so far as relates to the moon, which he supposes to have separated, not as a ring while the earth was still in an expanded gaseous condition, but as a lump, or as a series of fragments, after the earth had concentrated to a liquid or perhaps even an incipient solid state. By a beautiful mathematical investigation of the effect of a postulated body-tide of the earth upon the motion of the moon, he concluded that the moon has been forced to retire gradually from a position at or near the earth, to its present distance, in the course of its history. The tidal protuberance of the earth is carried forward by rotation, and so tends to draw the moon forward in its course. This causes the moon to take a larger orbit, while the backward pull of the moon on the tidal protuberance tends to retard the rotation of the earth. That the tides tend to force the moon to retire in some measure, is a sure deduction from the dynamics of tidal forces and the assumption of a body-tide, and hence it seems probable that the moon was originally nearer the earth than it is now; but how much nearer remains an open question on which we have already touched.[2] On account of its close relations to the earth, the origin and history of the moon are matters of great interest, but the different views that have been entertained cannot be pursued into detail at this point.

Supposed passage of the earth from the gaseous to the present condition.—The Laplacian hypothesis assumes that the earth-matter remained essentially in the gaseous condition until the heat of the central portion fell to the temperature of liquefaction of the more refractory matter, when a liquid nucleus formed. As cooling went on, this grew until the chief rock-substances had concentrated into a molten globe, while the more volatile material remained in a gaseous state and formed a vast hot atmosphere.

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[1] On the Secular Changes in the Elements of the Orbit of a Satellite Revolving about a Tidally-distorted Planet, Phil. Trans. Roy. Soc., Pt. II, 1880. Also, On the Tidal Friction of a Planet Attended by several Satellites and on the Evolution of the Solar System, ditto, Pt. II, 1881.

[2] Vol. I, p. 576.

The supposed crust.—It was formerly held that the next step was the crusting-over of this molten globe by surface cooling, and that this was followed by a progressive thickening of the crust. It was a common view that this state continued even down to the present day, and that the earth still consists of a liquid interior inclosed in a solid shell. The term "crust of the earth" arose from this belief, and it is still much used as the most convenient term for the outer part of the earth, even by those who do not attach the original meaning to it. Against this view it has been urged that solid lava is heavier than molten lava and should therefore sink to the center as fast as it formed. In reply it is urged that, in such a molten globe, the heaviest material would gather at the center, with successive layers of lighter and lighter material above it, the lightest of all being at the surface, so that, even though the solidified portions of this lightest layer were heavier than their own liquid stratum, and so would sink through it, they would still be lighter than the heavier liquid layers below, and would thus be arrested by them. These sunken portions might be remelted for a time, but the process would at length so cool the whole outer layer that remelting would cease, and a subcrust would form which, in time, would be built up to the surface and give a complete crust formed of the outermost layer of light material. In pursuance of this view, it was supposed that the granitic group, the lightest class of igneous rocks, formed the primitive surface, but this special view has been weakened by recent studies of the oldest known rocks.

Astronomical argument for solidity.—Arguments against a crust resting on a liquid bed have been brought to bear by physicists and astronomers who, reasoning from the phenomena of the tides, of the precession of the equinoxes, of variation of latitude and of nutation, have urged that the earth must be essentially solid; must, indeed, have a practical rigidity of a high order. The support of the continental platforms at a height of 12,000 to 18,000 feet above the ocean basins, as well as the support of the great plateaus and mountain ranges superposed on these, present other grave objections to the hypothesis of a liquid interior. To these last objections, the answer has been made that the continents, plateaus, and mountains are inherently lighter than the material of the ocean bottoms, and this seems to be essentially true. To the astronomical argument it has been replied, in part, that a stiff liquid inclosed in a thick shell and rotating rapidly would act toward a transient external force as though it were a solid.

Notwithstanding these answers, the opposing considerations have greatly reduced the number of adherents of a molten interior, among whom were once embraced the great body of geologists. The view is still held, however, by eminent geologists, and—what is more needful to note—it remains embodied *unwittingly* in many doctrines relating to the interior and to its dynamics which are held by those who have ceased to hold the parent view. A striking example of this is found in the thermal discussions of Lord Kelvin and others in which a uniform temperature in the deep interior is assumed. This is really a corollary of the conception of surface cooling and convection, and apparently can have no other basis. Yet it has entered profoundly into nearly all the fundamental doctrines of deformation. Its bearings have been indicated in Vol. I, pp. 559, 560.

Supposed solidification from the center outward.—For substances which shrink in solidifying, as do most rocks, it is a general law that the melting-points are raised by pressure. Out of this has grown the doctrine that solidification due to pressure would begin at the center of the earth while yet the outer part was liquid. This view has been much strengthened by the experiments of Barus and others.[1] Under such pressure as could be applied, Barus found the rise of the melting-point of a typical rock (diabase) to be directly as the pressure. Extended by computation to the center of the earth, the melting-point would be 76,000° C. It is of course uncertain whether the law would hold good throughout the extraordinary conditions of the deep interior, and little weight is to be attached to the precise figure given, but the general deduction is of fundamental importance. As this doctrine of solidification under pressure, in spite of heat, seems to have the support of the best available experimental data, and as it meets the astronomical and topographic arguments for a solid earth, it has come to have wide acceptance. Under this general view, it is held by some that the solidification continued outward from the center until the surface was reached, and that the surface cooled last of all, a conclusion precisely the opposite of the old view.

Supposed middle molten zone.—By others it is thought that crusting over at the surface took place before the central solidification reached the surface, and that there was then a zone of liquid between a solid crust and a solid center. This zone is thought by some to have remained to the present time; by others to have solidified later, and by still others to have partially solidified so that the crust is joined to the central mass by solid supports, while residues of liquid have been left between in certain portions. By postulating these liquid residues, a source for the lavas ejected at later stages is hypothetically provided.

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[1] U. S. Geol. Surv., Bull. 103. See also Vol. I, this work, pp. 562–564.

Hypothetical gaseous center.—Against the view of a solid center it is urged that the temperature of the gaseous globe at its center must have been above the critical point, and must have risen with progressive condensation so long as it remained in the gaseous state, and hence that the gaseous center could not have taken on the solid state. A globe with a gaseous center is therefore a fourth conception. How this is to be reconciled with the evidences of rigidity and other physical phenomena of the globe is not obvious.

There thus arise from the Laplacian hypothesis four general conceptions of the state of the body of the earth: (1) that it is all liquid within and merely crusted over, (2) that it is solid at the center and crusted over on the surface, with a liquid or partially liquid zone between, (3) that it is solid throughout, and (4) that its center is gaseous and its exterior solid.

Part played in geologic doctrines.—The view that the earth was once in a molten state very naturally led to certain inferences as to the internal arrangement of the matter, the original form of the surface, the state of the primitive atmosphere, and to a long chain of dependent interpretations; and so the hypothesis has become interwoven with the interpretations of nearly all the great phenomena of geology. The changes in the form of the earth, the warping of its crust into ocean basins and land protrusions, its wrinkling into mountains, its fissurings and faultings, its risings and fallings, its volcanoes and its earthquakes, have been usually regarded as the natural sequences of a cooling globe. So, too, the consumption of the atmosphere in the formation of the oxides, carbonates, and carbonaceous deposits, and the absorption of the ocean into the body of the earth, are current doctrines founded on the Laplacian hypothesis.

Supporting phenomena.—In favor of the Laplacian hypothesis stand the unquestioned facts that the interior of the earth is hot, that molten rock has been extruded from it at various times throughout the known geologic ages, and that the earliest known rocks are largely igneous or igneous derivatives. In its favor also has been cited a long list of beautiful harmonies in the solar system, whose features of symmetry have been thought to tally well with the orderly separation of its members as successive rings.[1]

Objections to the Laplacian hypothesis.—Notwithstanding the very general acceptance of the Laplacian hypothesis during the past century, certain objections have all along been urged against it, and recently certain new ones of a cogent nature have been pressed upon consideration.[2]

(1) As already noted, it has been urged that definite rings might not be formed, but that the equatorial matter would more probably separate particle by particle.

(2) It has been questioned whether the rock substance of the earth in the attenuated condition it must have had in the supposed earth-moon ring would not have cooled to solid particles long before it could have collected into a spheroid.

(3) By mathematical investigation, Moulton has recently shown that there are grave mechanical difficulties in the contraction of a ring into a spheroid as simply and promptly as supposed by Laplace, and this gives new point and force to the preceding objection.

(4) It has been urged that in so highly heated a condition as the hypothesis assumes, the molecular velocities of the lighter gases of the ring would be so great that they could not be held together by the attraction of the ring, and perhaps could not be controlled even by the gravity of the supposed gaseous spheroid.

(5) It is a most singular fact that Phobos, the inner satellite of Mars, revolves in less than a third of the time of the planet's rotation, whereas, according to the Laplacian theory, the planet's rate of rotation should have kept on increasing after the ring that formed

[1] A full list of these is given in World Life by Alex. Winchell.

[2] A Group of Hypotheses bearing on Climatic Changes, Jour. Geol., Vol. V, No. 7, 1897, pp. 653–83; An Attempt to Test the Nebular Hypothesis by the Relations of Masses and Momenta, Jour. Geol., Vol. VIII, No. 1, January-February, 1900, pp. 58–73; Certain Recent Attempts to Test the Nebular Hypothesis, Science, Vol. XII, August 10, 1900, T. C. Chamberlin; An Attempt to Test the Nebular Hypothesis by an Appeal to the Laws of Dynamics, Astrophys. Jour., Vol. XI, No. 2, March, 1900, pp. 103–130, F. R. Moulton.

Phobos was detached. To explain this difficulty, G. H. Darwin has suggested that tidal retardation may have decreased the planet's rotation much more than the contraction increased it, but this seems highly improbable. Furthermore, Moulton has shown that the particles that make up the inner edge of the inner ring of Saturn revolve in about half the planet's time of rotation, and that the tidal argument, applied to Mars, does not fit this even more singular case without making new and inconsistent assumptions.[1]

(6) But perhaps the most severe test to which the Laplacian hypothesis has recently been subjected is founded on a study of the relations of mass and momenta. It is a firmly established law of mechanics that the moment of momentum of any freely rotating or revolving system, like the nebula in question, remains constant, if not influenced from without, whatever changes the system may undergo; and this principle is peculiarly well adapted to test the evolution of the solar system. Now Moulton has shown[1] that if the solar system be converted into a gaseous spheroid, so expanded as to fill Neptune's orbit, and so distributed in density as to conform to the recognized laws of gases, and if the whole moment of momentum now possessed by the solar system be given to it, it will not have a rate of rotation sufficient to detach matter from its equator, and would not acquire such a rate until it had contracted well within the orbit of the innermost planet.

(7) If the method be reversed and the expanded spheroid be given the successive rates of rotation necessary to develop the rings at the requisite stages, the moment of momentum of the system at each ring's birth should equal the existing moment of momentum of the derived bodies. But Moulton's computations show that, at the stage that gave birth to the Neptunian ring, the moment of momentum of the restored nebula must have been more than 200 times as great as the present moment of momentum; in the Jovian stage, it must have been 140 times as great; in the earth stage, 1800 times as great, and in the Mercurial stage, 1100 times as great. Here is not only an enormous discrepancy, but one that varies greatly and irregularly from stage to stage. This seems to show that the discrepancies cannot be due to any failure of the law of density of gases to hold good, for that should give a consistent systematic error.

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[1] Loc. cit.

(8) So again, if the ratios of the masses separated at the successive stages be compared with the momenta they carried off, very remarkable discrepancies arise. In this case the moment of momentum of the parent nebula at any stage may be computed from the moments of momentum of its derivatives, and so all doubts that may arise from the distribution of density in the nebula be avoided. For example, the mass of the supposed ring that formed Jupiter and his moons was less than one-thousandth part of the solar nebula at the stage at which the ring was separated; but Jupiter and his moons now have about 95% of the total amount of moment of momentum of the whole nebula at that stage. In other words, the Laplacian hypothesis involves the proposition that in a rotating gaseous spheroid, an equatorial ring equal to less than one-thousandth of the whole mass, in separating by centrifugal acceleration, carried off 95% of the whole moment of momentum, which seems incredible. A similar examination of the separation of other rings gives like extraordinary results, and these results, as in the previous case, vary greatly and irregularly among themselves, showing a lack of system or consistency in the supposed process of ring detachment.

The inquiry along these lines, being of a somewhat rigorous mechanical nature, throws grave doubt on the validity of the Laplacian hypothesis. It seems to show that the solar system must have been organized so that a very small fraction of the matter (i.e., the planets and satellites, which amount to about 1/700 of the whole system) carry nearly all (97+%) of the moment of momentum, leaving less than 3% in the central body that carries all of the matter but the minute fraction named. It is difficult to see how this could arise from a rotating spheroid. Tidal reaction, by transferring momentum from the central to the outlying bodies, may help slightly to escape from the difficulty, but computation shows that it is utterly inadequate to meet the case.

(9) Under the Laplacian hypothesis the satellites should all revolve in the direction in which their planets rotate. The newly discovered ninth satellite of Saturn revolves in a direction opposite to the planet and the inner satellites.

Unfavorable testimony of existing nebulæ.—The hold of the Laplacian hypothesis has been still further weakened by the fact that, though the knowledge of existing nebulæ has recently been extended very greatly by photography, nebulæ have not been found which present a series of such systematic annulations as the hypothesis postulates. On the contrary, the spiral nebula, as announced by the late Professor Keeler,[1] is found to be the dominant type.

II. The Meteoritic Hypothesis.

A simple but untenable form.—It was long ago noted that, from time to time, fragments of stony and metallic matter fell from the heavens, and that shooting stars entered the upper atmosphere nightly in great numbers; and out of this naturally grew the suggestion that the earth may have been built up in this way, save that the process was rapid in the early ages before the heavens had been so thoroughly swept of meteoritic material. This form of the hypothesis, however simple and natural, may be dismissed without serious consideration, for the distribution of meteorites, their directions of motion, and their velocities are such as to forbid the belief that the solar system, with its symmetrical discoid form and its many peculiar and significant features, could have been formed from them *directly* in the manner supposed.

The hypothesis of Lockyer and Darwin.—In a work entitled "The Meteoritic Hypothesis" Lockyer has endeavored to show that nebulæ are composed of meteorites sparsely aggregated into swarms, and that stellar systems are evolved from them. His hypothesis is, therefore, nebulo-meteoritic, and relates to a stage antecedent to the formation of the planets. He assigns the light of the nebulæ to the collision of the meteorites with one another. To meet the fact that the spectra of some nebulæ are of the gaseous type, he assumes that the impact vaporizes a part of the meteorites, and these vaporized portions give forth the gaseous spectra. It remains to be explained, however, why the spectra of these nebulæ rarely show anything but hydrogen, helium, and an unknown substance, or substances, provisionally called nebulium, and are never known to show metals. The continuous spectra which other nebulæ present he refers to the solid or liquid portions set aglow by collision. The luminosity of any given meteorite arising from impact must be very transient, but the hypothesis assumes that the aggregate result of many such collisions is a nearly constant emanation of light. Lockyer's treatise does not enter into a definite discussion of the mechanics involved in the original gathering together of the nebular swarm, nor does it attempt to trace the course of evolution down to the origin of the planets and the specific genesis of the earth.

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[1] Astrophysical Journal, June, 1900, pp. 347, 348.

In a very notable paper,[1] George H. Darwin, starting with such a swarm *already aggregated* and already possessed of a mass and a distribution suited to the formation of the solar system, has elaborately discussed its mechanical characters. The essential result of his laborious inquiry is the conclusion that such a swarm is dynamically analogous to a gas, and that the laws governing gases may be applied to the discussion of its mechanical properties. He does not attempt to carry the history forward into the development of the planets, but apparently believes that they arose from equatorial detachment, as in the Laplacian hypothesis. In its immediate application to the origin of the earth, this special form of the meteoritic hypothesis seems therefore to become practically identical with the gaseous hypothesis, and hence to be subject to the criticisms urged against that hypothesis, notably those arising from the relations of mass and momenta, which seem to be the most grave.

There arises also the question whether such a swarm of meteorites would not *actually pass into the gaseous condition,* as the result of the heat developed by the frequent and violent collisions of the meteorites. To the swarm under investigation, Darwin assigned a radius 44½ times the radius of the earth's orbit, which involves a quite attenuated dispersion. At even this dispersed stage, he computed that collisions, in the region of the present earth's orbit, would occur at a rate of ten or more per day, and at an average velocity of three or more miles per second. With this frequency and velocity, it would seem that the meteorites could not long escape comminution and vaporization. As the comminution and vaporization progressed, and as the nebula condensed, the frequency of the collisions must have increased, and the escape of the augmented heat, so caused, must have been more and more obstructed. The logical conclusion seems to be that an actual passage into the gaseous condition would ensue.

As this form of the meteoritic hypothesis thus appears to merge into the gaseous one, dynamically, if not literally, before the birth-stage of the earth is reached, it is not needful to follow it further here, where the origin of the earth is the subject of quest.

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[1] On the Mechanical Conditions of Swarms of Meteorites and on Theories of Cosmogony, Phil. Trans. Roy. Soc., 1888.

Is some other form of the meteoritic hypothesis tenable?—Is it possible to postulate, on probable grounds, some other phase of meteoritic assemblage that will continue to be meteoritic throughout its evolution down to the formation of the earth, and give distinctive geologic results? Prolonged efforts on the part of one of the authors to frame such a hypothesis, in definite terms and in a workable form, have been attended by unsatisfactory results only. The difficulties are very grave. On the one hand are dispersive agencies that tend to keep up the scattered condition of the meteorites and to prevent assemblage; on the other hand, if a tendency to assemblage be established, the growing swarm seems sure to merge either into the gaseous or quasi-gaseous condition, as above outlined, or else into the planetesimal system presently to be considered. The true meteoritic condition appears to be an expression of a dispersive function which tends to produce and to perpetuate a scattered state. An adequate discussion of the possibilities and limitations of meteoritic assemblage is beyond our limits, but there are involved certain fundamental facts and principles of no little importance to the philosophic student of geology who wishes to probe, as well as he may, the basal postulates of the earth's genesis, and these merit attention. The subject, to be sure, is essentially astronomical, but as geology is the domestic chapter of astronomy, the geological student is entitled to go as far afield as his problem requires.

The two general conceptions of the origin of the meteoritic state.—Conceptions of the ulterior origin of the dispersed condition from which evolution may be supposed to start, fall into two general classes: (1) a primitive diffuse condition, without previous assemblage, a kind of original chaos; or (2) a derived condition of dispersion arising from the scattering of previous assemblages or the disruption of previous bodies. If in the second case the dispersion be so great as to project the disrupted material beyond the sphere of its own gravitative control, its condition becomes dynamically the same as if it originated in such a dispersed condition. It is therefore only necessary to consider those cases of this class in which the scattered matter remains under its own gravitative control and constitutes a diffuse flock or swarm of small bodies.

1. *Assemblage from a Primitive State of Dispersion.*

Conditions affecting the initiation of a meteoritic swarm.—The starting of a meteoritic swarm, theoretically, from dispersed meteorites moving in diverse directions, as typical meteorites do, encounters a grave obstacle in *the high ratio of the kinetic energy of the meteorites to their mutual gravitation.* Since gravitation is the agency of assemblage, and the kinetic energy of their motion is the dispersing agency, it is obvious that if the potency of the latter is superior to that of the former, the conditions for gathering meteorites into a swarm are adverse, at least in general. The relations between the kinetic energy of meteorites and their mutual gravitation therefore require consideration as a basal feature.

The velocities of meteorites.—While the velocities of meteorites have been only approximately ascertained, between those that have been directly measured and those that have been estimated from incidental facts, they are sufficiently well known for the purposes of general discussion. The meteorites which are seen in the evening strike the earth from behind, and since the earth is moving in its orbit at an average rate of 18.5 miles per second, these meteorites must overtake it with a velocity sufficiently in excess of this to become incandescent in passing into the atmosphere. From present data, the average velocity of meteorites, when they encounter the earth's atmosphere, is estimated to be between 20 and 30 miles per second. Occasionally the velocity appears to reach 40 or 50 miles per second, and even more. The velocities of meteorites seem to be of the same order as the velocities of the stars, whose average has recently been placed by Newcomb at 23 miles per second. This of course is merely the average of those that have been thus far measured, and will doubtless be changed by additional measurements; but this velocity may be taken as roughly representative of the velocities of stars and of meteorites in this part of the sidereal system.

Now to give to the meteoritic hypothesis the best possible conditions, let all the matter of the sidereal system be supposed to be converted into meteorites, and let these meteorites have directions of motion and velocities identical with the parent bodies. It seems necessary to assign them these motions to preserve the moment of momentum of the system as the laws of mechanics require. We have thus a kind of primitive chaos in which movements in all directions, with velocities varying greatly, but averaging twenty odd miles per second, prevail. The critical feature is the prodigious kinetic energy which so high an average velocity involves.

Now the only effective known force which might draw these flying meteorites together into swarms and keep them together is their mutual gravitation. Electric and magnetic attractions might do a certain auxiliary work under special conditions; but as these attractions are accompanied by neutralizing electric and magnetic repulsions, the differences between them may probably be neglected.[1] We must, therefore, inquire how the controlling power of gravity compares with the amount of kinetic energy that must be overcome.

The mutual gravitation of small bodies is extremely feeble. For example, Moulton has computed that if two spheres having specific gravities of 10 and diameters of 10 feet, and hence each weighing 164 tons, be placed 100 feet apart and be wholly unaffected by any other force than their mutual attractions, practically half a day (11.66 hours) will be required for them to draw themselves together, when each has to go only 45 feet. Their mean velocity is therefore less than four feet per hour, a scarcely perceptible motion. If they were separated to an infinite distance and allowed to fall together, and thus to develop the highest possible velocity which their mutual attraction could produce, it would not exceed .012 feet per second (Moulton). It is obvious, therefore, that if the supposed primitive meteorites moved at the assigned velocities, or at velocities even remotely approaching them, they would be quite beyond the gravitative control of one another individually. Such meteorites, moving in opposite or transverse directions, would pass by one another without appreciably deviating from their courses, unless they chanced to collide. In that case they would probably be shattered and dispersed, because on the average they would strike at velocities many times as great as the projectiles from the best modern guns. If they remained unbroken, they would, if perfectly elastic bodies, exchange velocities and directions, or, if perfectly inelastic bodies, would combine their momenta, unless they were driven apart by the explosive force of vapors formed at their points of impact, as suggested by Darwin. As most bodies are neither perfectly elastic nor perfectly inelastic, an intermediate result would usually follow. In exceptional cases, the velocities might be low enough to permit inelastic bodies to weld together, but apparently the chances of disruption, or of elastic rebound, would be many times greater than those of welding. Even in the case of welding, the result is merely a larger meteorite in lieu of two smaller ones, and no progress is made in the starting of a meteoritic *swarm*. Besides, the enlarged meteorite is subject to disruption by succeeding violent collisions.

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[1] We are here speaking of the ordinary phenomena of electrical and magnetic attraction and repulsion, as commonly understood; not of those newer and profounder interpretations which assign inertia and other phenomena, including even gravitation itself, to electromagnetic agency; much less the radical views involved in the electromagnetic theory of matter.

The possibilities of parallel movement. — Apparently the only working chance of starting a swarm of meteorites by attraction, under these adverse conditions, lies in the exceptional case of meteorites moving in nearly parallel directions, at nearly the same speed, and in courses near one another. In this case the motions of the meteorites only antagonize their mutual attractions to the extent of such small differences of kinetic energy as may arise from their slight differences of velocity and directions of motion. Under extremely favorable conditions of this kind, two meteorites might come into mutual gravitative control and revolve about their common center of gravity. Then a third one might join them under like conditions, and so on. But the plane of revolution of the third meteorite might chance to correspond with that established by the pair it joined, or it might not. So also its direction of revolution might or might not be the same. It is therefore extremely unlikely that the planes of revolution of any considerable number of meteorites, coming thus together, would be even approximately identical, or that the directions of their revolutions would be coincident, and hence opposite and cross revolutions would result, with obvious liability to collisions, so that, in the end, the swarm would perhaps develop into a quasi-gaseous condition.

A possible alternative, if the material were sufficiently inelastic, might be the mastering and killing out of the movements of the minority of the group by the majority through a long series of collisions, and the development thereby of a common direction of revolution, in which case the system would take on the orbital, rather than the gaseous type, and fall under the planetesimal class.

The danger of dispersion.—It must be noted, however, that the conditions for starting the growth of such a swarm—nearly parallel adjacent movements at nearly equal speeds—are very exceptional, and hence the accessions in any given period must be presumed to be few compared to the whole number of meteorites that pass the place of the initiating swarm; for all those that have opposite and transverse courses of any appreciable angle, and all those that, though moving in parallel directions, have appreciably different velocities, will pass through the point of assemblage with dangerous differential velocities. They are therefore liable to break up the initiating swarm by colliding with its members and driving them beyond its gravitative control. This contingency is especially great while the swarm is small, and its gravitative command of its members feeble. Hence arises the question whether the swarm's peril of destruction is not greater than its chance of growing to a self-protecting size, so incomparably greater, indeed, as to render the method an extremely improbable one.

If such a swarm succeeds in reaching a large mass, the probabilities of its holding its own members and of capturing the colliding meteorites, become very favorable. The growth of a meteoritic swarm or of a nebula *after it has once gained a sufficient massiveness*, is therefore simple enough and probable enough; but the starting of a swarm, and the early stages of its growth, are attended by extremely unfavorable contingencies.

The sparseness of distribution and its bearing.—The extreme tenuity of the celestial matter hypothetically thus dispersed is another vital consideration. The light of a star in a flight of 50 years, at the speed of 186,000 miles per second, does not seem, on the average, to encounter enough dark matter to seriously dim its brightness. All the matter that lies between us and the outermost visible stars does not cut off as much light as the thinnest cloud. On a most liberal estimate of the amount of meteoritic matter encountered by the earth at present, it is computed that it would take a billion years to add an inch to its surface.[1]

If all the matter now aggregated in the stellar system, on any reasonable estimate of its mass (and the known distribution and movements of the celestial bodies limit such an estimate), were distributed through the space now occupied by the stars, it would not help the case much, so far as meteoritic assemblage is concerned. To illustrate, if the matter of the solar system were scattered through the space about it, stretching out half-way to the nearest stars, its tenuity would be such that, if the orbit of Neptune were the hoop of a drag-net, 5,600,000,000 miles in diameter, and were sweeping through this space at the rate of 12 miles per second—the approximate velocity of the sun with respect to the stars—it would take some 900,000,000,000 years for it to sweep up the scattered matter. This is probably not an unfair illustration of the average tenuity of the supposed dispersion, since the star-grouping about the sun is probably as dense as the average of the whole. This tenuity immeasurably transcends the best vacuum of the most effective air-pump. It would be an extravagant license in the use of terms to call this a "meteoritic plenum." Misconception here is fundamentally dangerous. The matter in the heavens is extremely small in proportion to the space—almost inconceivably small. This extreme sparseness of distribution means that the potential energy in the stellar system is enormously great in proportion to the amount of matter. The factors then that weigh in the study of meteoritic assemblage are not simply, or even predominantly, matter and gravitation, but also, and particularly, space and motion.

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[1] Young's Astronomy, p. 475; Woodward, Astr. Jour. 1902.

The time factor.—With such excessive tenuity of dispersion, even when all known matter is converted into meteorites, and with such potent obstacles to assemblage as are imposed by the high kinetic energy of the meteorites, it seems an imperative conclusion that the growth of a meteoritic assemblage having the mass of the solar system must require a period quite beyond comprehension. This leads on to the question whether a swarm of meteorites could perpetuate itself, *as a swarm*, through such a prodigious period. Must not the part first assembled pass on through its own evolution, whatever that may be, without awaiting the excessively delayed assemblage of the later portions? If the members of the swarm were in collisional relations, as postulated by Lockyer and Darwin, must not the kinetic energy of the earlier assemblage have been exhausted long before the accession of the later part? In other words, must not the first assemblage become solid at a relatively early stage in the process, and the remainder of the accessions be added individually, as meteorites are now added to the sun and planets? Is it a tenable view that the mere assemblage of a swarm should go on, without attendant evolution, until the mass necessary for a solar system is attained, and then, *but not until then*, enter upon an evolution into a sun-and-planet system? If the swarm was organized on the collisional basis, nothing but a negative answer seems possible. If the meteorites could be supposed to come together so as to revolve in harmonious orbits about a common center, on the planetary basis, the assemblage might be perpetuated, but this takes the case out of the typical meteoritic class, and carries it over to the planetesimal.

Under the conditions of the case, it is not apparent how a meteoritic nebula of the quasi-gaseous or collisional type can grow up *de novo* by the assemblage of dispersed meteorites, or by the aggregation of chaotic matter, if the material were endowed with the present momentum of the system.

2. *Derivation from Previous Aggregates.*

If the origin of the nebula be assigned to the dispersion of some previous large body, three phases are conceivable: (*a*) dispersion by explosion, (*b*) dispersion by collision, and (*c*) dispersion by tidal disruption.

(*a*) **Dispersion by explosion.**—The diffuse state of the parent nebula may perhaps be assigned to explosion, following the analogy of one of the hypotheses of the origin of new stars, though it is difficult to assign any probable and adequate cause for such explosion. But if it takes place, the dispersing force must obviously be radial, in the main, and after the matter has made its outward excursion and is arrested by gravitation, it must return on nearly direct lines and collide at the virtual point of departure. The result of this collision, if the dispersion have nebular dimensions, must be the development of enormous heat and the probable conversion of the whole into a gaseous body. If so, the evolution must thence proceed along gaseous lines. In this case, nothing properly analogous to a meteoritic condition is likely to be developed in the system, except as a mere incident, and the case does not really belong under the meteoritic hypothesis. Such an explosion may indeed give rise to material shot away beyond the control of the system, and this part might be truly meteoritic, but it would be lost to the system, and fall under the case already discussed.

(*b*) **Dispersion by collision.**—If the dispersion be assigned to the collision of two large bodies, as postulated by Croll[1] and others, the heat developed must be presumed to be great enough to convert the main mass into a gaseous state. If the collision were a center-to-center encounter, a radial dispersal of matter transverse to the line of collision would follow; returning from which, the material would again collide, and after a series of oscillations would gradually settle down into a pulsating gaseous mass.[1] Here again the system would become gaseous at the outset, and probably develop nothing of the typical meteoritic kind except possibly such sporadic elements as might be projected beyond the control of the system. If the collision were excentric, a rotatory motion would doubtless be superposed upon the radial motion, and the case would either fall under the gaseous or the orbital system, or under a combination of the two.

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[1] Croll, Climate and Cosmology, 1889, pp. 297–315.

(*c*) **Dispersion by tidal disruption.** — It has recently been suggested that bodies passing close by one another, but not colliding, may suffer disruption through their differential attractions aided by internal elasticity,[2] on the principles developed by Roche, Maxwell, and others. In this case the disrupted elements are given a rotatory movement in a common direction and in the plane of the two bodies initiating it. The dynamics of the system are therefore from the outset definitely of a rotatory or revolutionary kind, and the case falls under the orbital or planetesimal system rather than the meteoritic system.

It appears, therefore, that neither explosion nor collision nor tidal disruption is likely to give rise to a distinctively meteoritic swarm, and no other definite source is known to us. *Individual* meteorites and rotatory or revolutionary assemblages of dispersed elements, as well as true gaseous nebulæ, may be supposed to arise from the catastrophes named, but apparently these catastrophes are not appropriate agencies for producing fragmental *swarms* of the distinctively meteoritic type.

The Evidence of the Meteorites Themselves.

The origin of meteorites bears on the question whether they are the essential material from which stellar systems are derived, *or are*

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[1] A case of this kind is described by Kelvin, Popular Lectures and Addresses, I, 1891, p. 413.

[2] On the Possible Function of Disruptive Approach in the Formation of Meteorites, Comets, and Nebulæ, T. C. Chamberlin, Astrophys. Jour., Vol. XIV, 1900, pp. 17–40, and Jour. Geol., Vol. IX, 1901, p. 369.

merely the incidental products of such systems, and dependent on the pre-existence of the systems.

Theories of the origin of meteorites.—Meteorites have been regarded (1) as matter projected from the earth by volcanoes and brought back to it, (2) as matter discharged from the moon, (3) as matter ejected from the sun or from stars, (4) as dispersed matter from exploded stars, (5) or from exploded planets or satellites, (6) as the residue of scattered comets, (7) as fragments of tidally disrupted atmosphere-less bodies, such as asteroids and satellites, and (8) as accretions of gas or fine particles of matter in open space.[1] All but the last pre-suppose the existence of the present solar system. Some of them further assume, by implication, that the meteorites constitute merely minute detachments from the present system. A volcano cannot shoot away any great part of the body of which it is itself, at best, but a small dependency. Only those dispersive hypotheses of this group that postulate the disruption of suns or stars carry any presumption that suns or stars would again be formed from them, for lack of mass. The last hypothesis alone assumes a *primary* organization. If meteorites are collected in space, as rain-drops are gathered in the atmosphere, and if they then unite to form solar systems, either through nebulæ or more directly, they are the source of such systems in as true and radical a sense as rains are the sources of lakes. The characters of meteorites should decide between these alternative views.

The characters of meteorites.—Among the distinctive and significant characters of meteorites are: their fragmentary forms, their brecciated structures in part, their occasional slickensided surfaces, their veins, the glassy nature of a part of their material, the amorphous nature of another part, and the crystalline nature of still a third and larger part, the variations in the coarseness of the crystallization, the extraordinarily large crystals of the nickel-iron, the inclusion of non-metallic crystals and nodules in the nickel-iron crystals, the scattered condition of iron crystals or lumps among silicate crystals in many cases (sporadosiderites), the large proportions of the nickel-iron and the magnesia, the presence of peculiar spheroidal aggregations (*chondri*), the fragmental nature of the chondri in many instances, the absence of water and hydrates, the absence of free oxygen, the absence of a group of minerals common in terrestrial igneous rocks, viz., quartz, orthoclase, the acid plagioclases, the micas, the amphiboles, leucite and nephelite, the presence of certain unstable chlorides, sulphides, and phosphides unknown in the earth, and the presence of volatile and combustible hydrocarbons.

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[1] For an excellent summary of the structure, constituents, and theories of meteorites see Farrington, Jour. Geol., Vol. IX, 1901, pp. 51, 174, 393, 522, and 623.

The bearing of these characters.—These make up a remarkable group of characters, whose origin can only spring from an equally peculiar combination of conditions.

While the fragmental condition of many meteorites, on reaching the earth, is due to fracturing in their passage through the air, there are indications that they already had a fragmental form when they

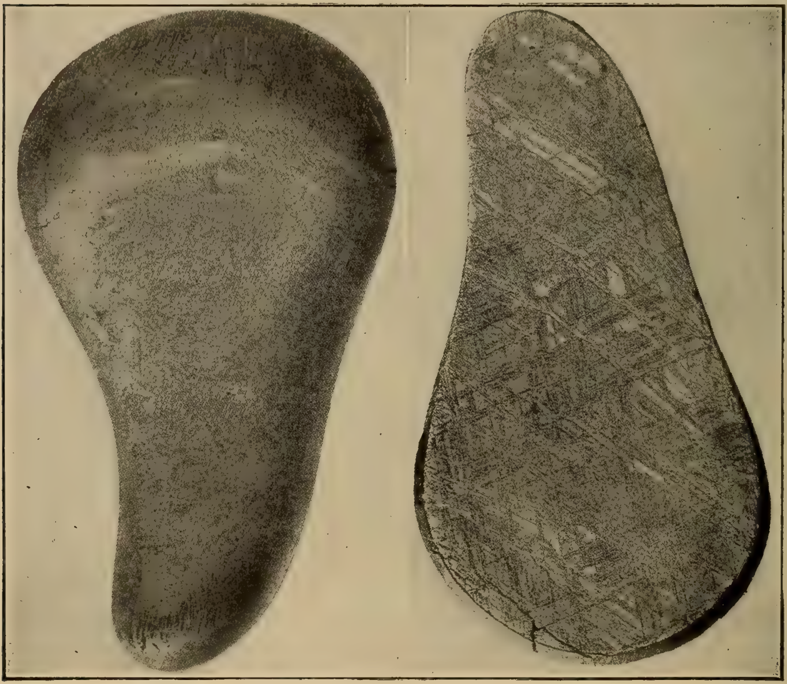

Fig. 1. Fig. 2.

Figs. 1 and 2.—A meteorite of exceptionally symmetrical form and smooth surface; one of the very few whose external form suggests a possible accretion in free space, and here introduced on that account. The truncated crystals of the cross-section, Fig. 2, however, show that it is reduced from a larger mass of unknown form. The coarseness of the nickel-iron crystals and their arrangement give no suggestion that the mass grew by accretion from a central nucleus. The Boogaldi (nickel-iron) meteorite, 3×5 inches. New South Wales. (After A. Liversidge.)

entered the atmosphere in many, if not most, cases. This implies that they are portions of larger bodies, and that they were not aggregated, as such, in free space (Figs. 1, 2, 3, and 4). At least this appears true in the case of most of the more massive meteorites that reach the surface of the earth. This of itself does not exclude the view that meteoroidal aggregation may take place in free space, and that the aggregates may have entered into the make-up of the larger body from which the meteorites were derived. It, however, bears on the question whether meteorites, as a rule, were organized, as such, by the

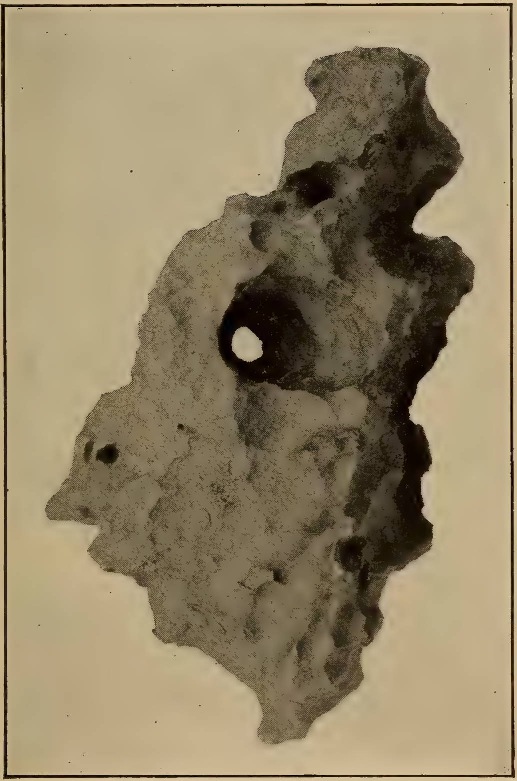

FIG. 3.—A nickel-iron meteorite of irregular form, showing obviously that it is but a fragment or remnant. The pits of the surface are due to the removal of the less stable material, probably silicates or metallic compounds, by which the nickel-iron was surrounded. Canyon Diablo meteorite, 265 lbs. Field Columbian Museum. (Photo. by O. C. Farrington.)

gathering together of gaseous matter or scattered particles in open space.

More direct evidence is found in the fragmental structure of many of the stony meteorites. Among the broken elements are fragments of chondri (Fig. 5). As the chondri are aggregations peculiar to meteorites, their fragmentation implies disruption and re-assemblage in the parent body, or at least disruption in an earlier stage of their history. Point is added to this by the occurrence of larger chondri enclosing fragments of smaller ones (Fig. 6). A very singular case of breccia is presented by the Mount Joy meteorite, which is an aggregate of iron fragments (Fig. 7). These various evidences of fragmentation imply a previous history affected by successive conditions of accretion and fracturing.

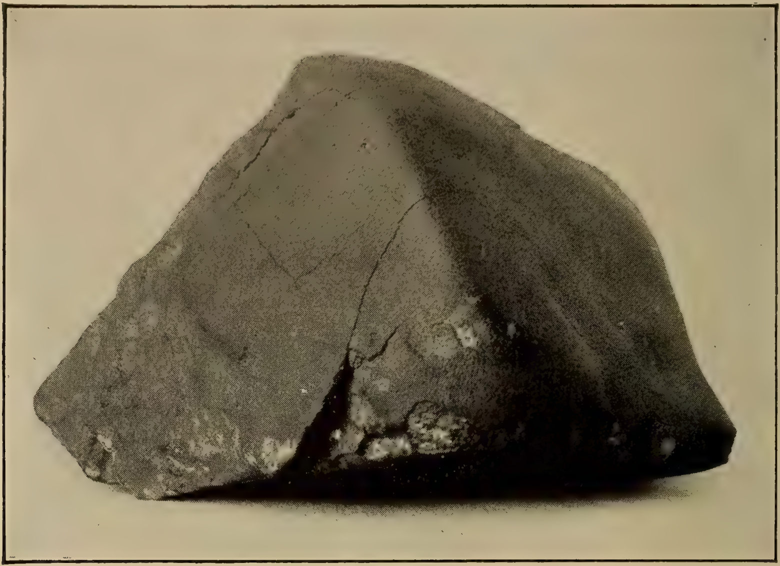

FIG. 4.—A stony meteorite showing fragmental outline smoothed by fusion in passing through the air, with smaller fracture surfaces due to exfoliation later in its course. The Saline, Kans., meteorite. Field Columbian Museum. (Photo. by Farrington.)

The presence of slickensided surfaces (Fig. 8) implies a parent body subjected to varying stresses, resulting first in fracture, and afterwards in the rubbing of the fissure walls upon one another. The existence of veins also implies fracture attended by subsequent filling.

The general prevalence, but partial absence, of crystallization, and the kinds of crystallization imply varied thermal conditions in the parent body. The amorphous condition implies the absence of fusion and of the conditions of crystallization. The glassy structure equally implies a molten state followed by quick cooling, while the various grades of crystallization imply high temperatures variously sustained. The extremely large crystals (Figs. 9 and 11) suggest protracted high temperature with conditions favorable for a systematic rearrangement of the material. At the same time the cases in which the metallic iron is scattered through the silicate material (Fig. 10) seem, at first thought, to imply the absence of a thoroughly fluid state at the time the segregation of the iron began, since a massing of the heavier metallic material toward the center of gravity would naturally be expected, just as in a blast-furnace metallic iron promptly separates from slag;

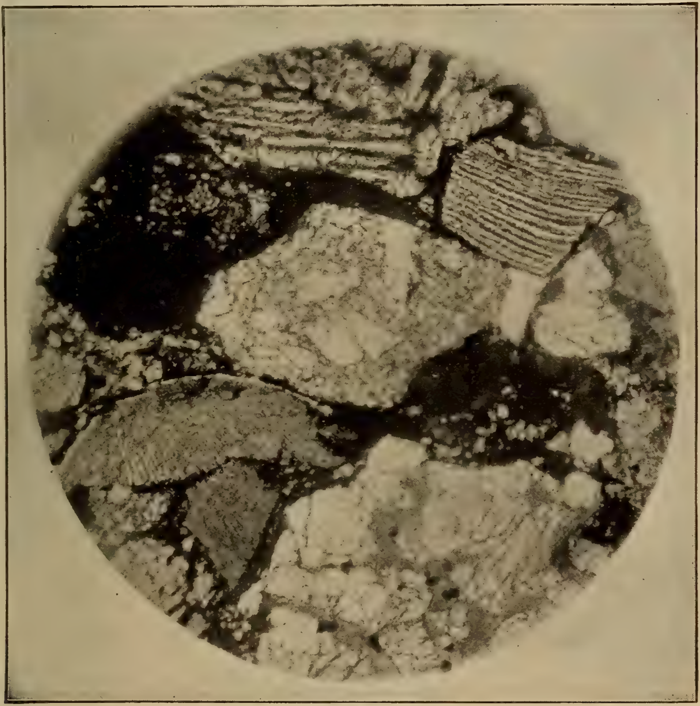

Fig. 5.—Section of the Mezo-Madaras meteorite, showing a meteoritic tuff made up of fragments of chondri. Portions of bronzite, chrysolite, and nickel-iron chondri can be recognized. (After Tschermak.)

but the presence of such scattered lumps of iron in the basalts of Greenland[1] at least limits the force of the inference. It suggests that either the mass was very viscous, or that the metallic material was very intimately diffused through the rock-substance previous to the beginning of crystallization, or that the motion of the molten mass was too great to permit gravitative segregation, or that these influences combined their effects. In addition, it is to be noted that a prolonged high temperature, acting on a mixed mass of material, may furnish conditions suitable for slow aggregation and crystalline rearrangement without the melting-point being reached, and that this also may be one of the agencies by which these singular combinations are produced.

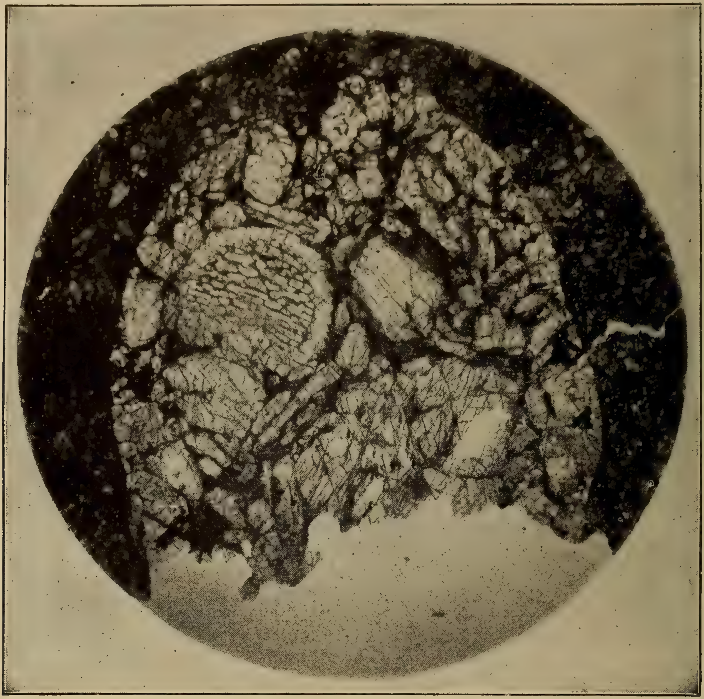

FIG. 6.—Section of the Dhurmsala meteorite, showing a large, somewhat porphyritic chondrus inclosing a smaller monosomatic one. Both are composed of chrysolite. ×8. (After Tschermak.)

It is hard to believe that these coarse crystallizations could have taken place in small masses of matter projected into space in the molten condition, and the view that meteorites are formed directly from lavas shot into space by volcanic or other explosive action, as from a sun, a planet, or the moon, is, therefore, unsatisfactory. Equally adverse to this view is the extraordinary fact that certain classes of meteorites are formed chiefly of *hydrocarbons* which are volatile at moderately high temperatures, and are readily combustible. These hydrocarbons seem prohibitive of high temperatures at all stages of their history, and it is a marvel that they should survive the transit through the atmosphere; but this is probably due to the fact that the meteorites were excessively cold when they entered the atmosphere and, during the brief time of transit, were only superficially consumed, while their interiors remained cold, as the interiors of meteorites are not infrequently found to be, immediately after their fall.

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[1] For a careful description and figures, see The Rocks of the Nugsuaks Peninsula, by W. C. Phalen, Smithsonian Misc. Coll., Vol. I, Pts. 1 and 2, p. 198, 1904.

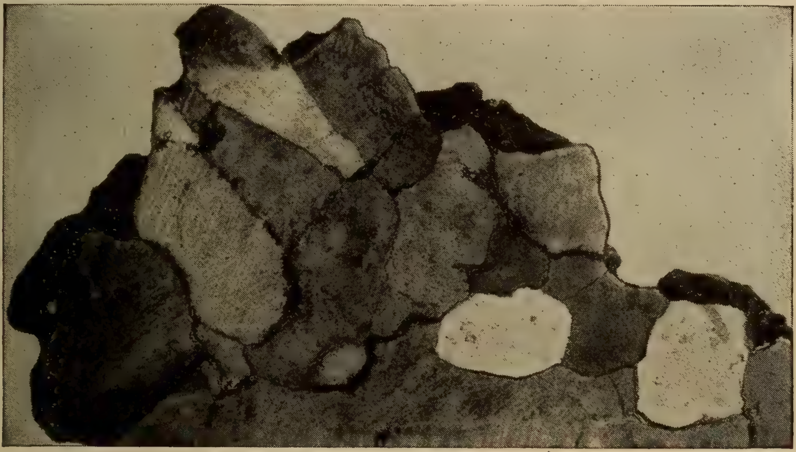

Fig. 7.—Section of the Mount Joy meteorite, nickel-iron, showing brecciated structure. Field Columbian Museum. (After Farrington.)

Igneous processes on the earth give rise to magmatic differentiation resulting in a familiar series of minerals which make up large portions of the crystalline rocks of the earth's surface. So also, weathering and solution remove more of the basic than of the acidic constituents of crystalline rock, and when the residue is metamorphosed, a similar series of minerals arises. Among these are quartz, orthoclase, the acid plagioclases, the micas and the amphiboles, a group absent from the meteorites. Their absence suggests that, in the parent body, magmatic differentiation of this kind, as well as selective weathering, did not take place. This, however, does not necessarily exclude volcanic action, nor nonhydrous weathering, but merely the dominant phases of weathering and magmatic differentiation that prevail in the earth, and probably in similar bodies having atmospheres and hydrospheres.

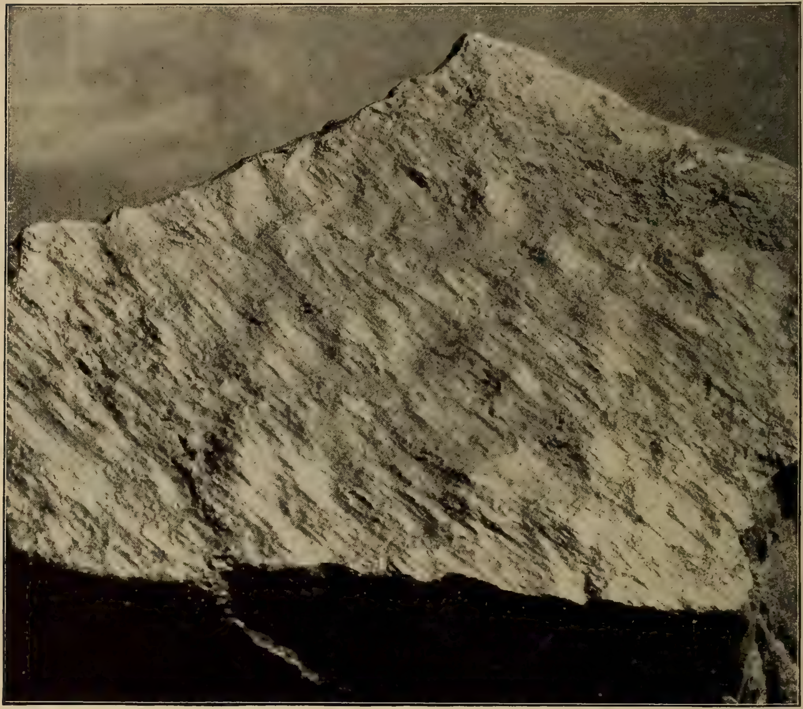

FIG. 8.—A slickensided surface of the Long Island meteorite, natural size. Field Columbian Museum. (After Farrington.)

The absence of water, of hydrates, and of free oxygen adds its testimony against the derivation of the meteorites from the crusts of bodies like the earth.

The high velocities and the diverse directions of the meteoritic flights relative to the earth forbid assigning their origin, in general, to volcanic action in the moon or any of the planets. Sufficient velocity might be given by a solar explosion, but the directions would be radial and not promiscuous. Explosive action within the solar system may have made an occasional meteoroidal contribution, but scarcely more than that.

Taken altogether, the combination of characteristics presented by meteorites seems to fail of satisfactory explanation on any hypothesis of their direct derivation from a sun or star, or from a planet surrounded by a hydrosphere or an oxygen-bearing atmosphere, or from any planetary body affected by mineralogic differentiations of the terrestrial type. No more do they seem to find satisfactory explanation in simple accretion in free space.

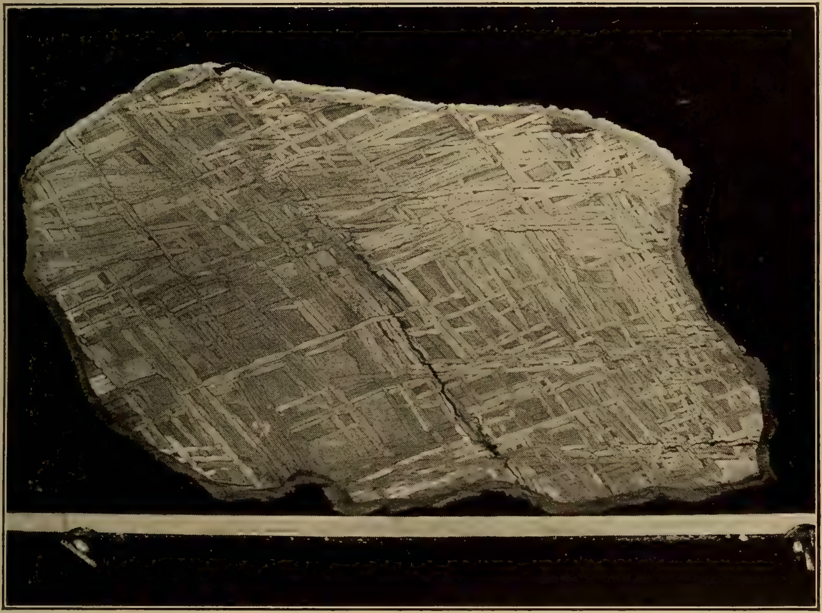

Fig. 9.—Section of the Franceville meteorite, showing the coarse crystallization of the nickel-iron (Widmanstätten figures). Ward-Coonley Collection. (From H. A. Ward.)

Possible derivation from atmosphereless bodies. — It remains to inquire whether small, atmosphereless bodies, like the asteroids and the satellites, afford a more probable source, or whether new hypotheses must be sought. Small celestial bodies are believed to be devoid of atmospheres and hydrospheres because their gravity is too low to overmatch the molecular velocities of the atmospheric gases and the vapor of water. This interpretation carries the corollary that they never have had permanent atmospheres and hydrospheres. They thus meet the requisite explanation of the absence of oxygen and water. If built up by accretion, they should contain the requisite variety of material, and, if formed in some other way, they might contain such variety. In their different parts, they may present the required structural characteristics. The asteroids and satellites are undoubtedly subject to deformations, attended by fractures, brecciation, veins, slickensides and similar dynamic phenomena. Eruptive and explosive action, as well as the impact of bodies falling from the exterior, may have contributed the various forms of fragmental, amorphous, and glassy material. The absence of a protecting atmosphere exposes their surfaces to the full striking force of falling bodies, and also the disrupting effects of extreme changes of temperature. On the exterior, and at slight depths, amorphous material, as well as glassy and cryptocrystalline rock, may have been formed. At greater depths, the varying conditions of pressure and temperature requisite for more complete and coarser crystallization may have been possessed. The hydro-

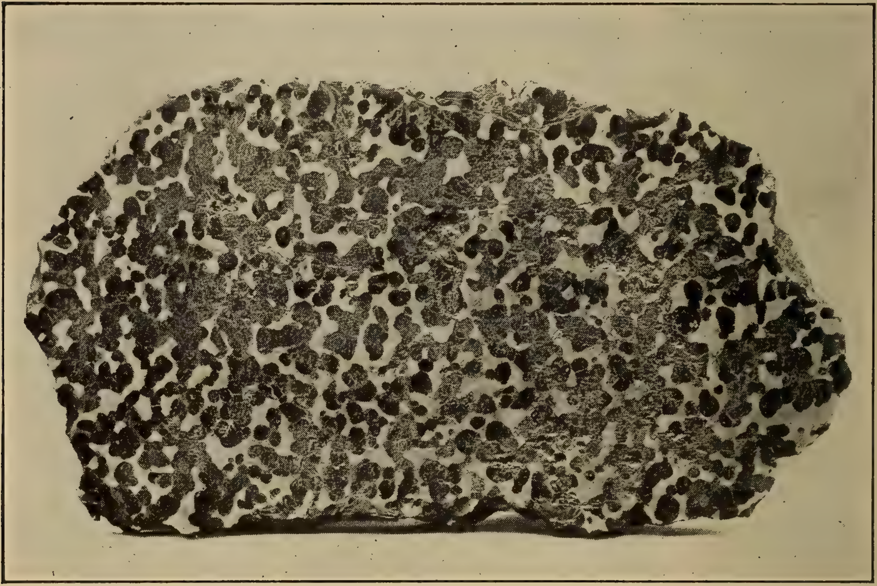

Fig. 10.—Section of the Brenham, Kans., meteorite, showing an intimate intermixture of nickel-iron, the light-colored portion, and silicate and metallic compounds, the dark portion. Ward-Coonley Collection. (From Ward.)

carbons may be assigned to inorganic action within the asteroidal body, the material being derived from the hydrogen and carbon gases so abundantly occluded in meteorites and crystalline rocks, the requisite temperatures and pressures being supplied by the internal compression of the body.

In these small bodies, then, it is perhaps possible to find that extraordinary combination of conditions which the nature of the meteorites implies.

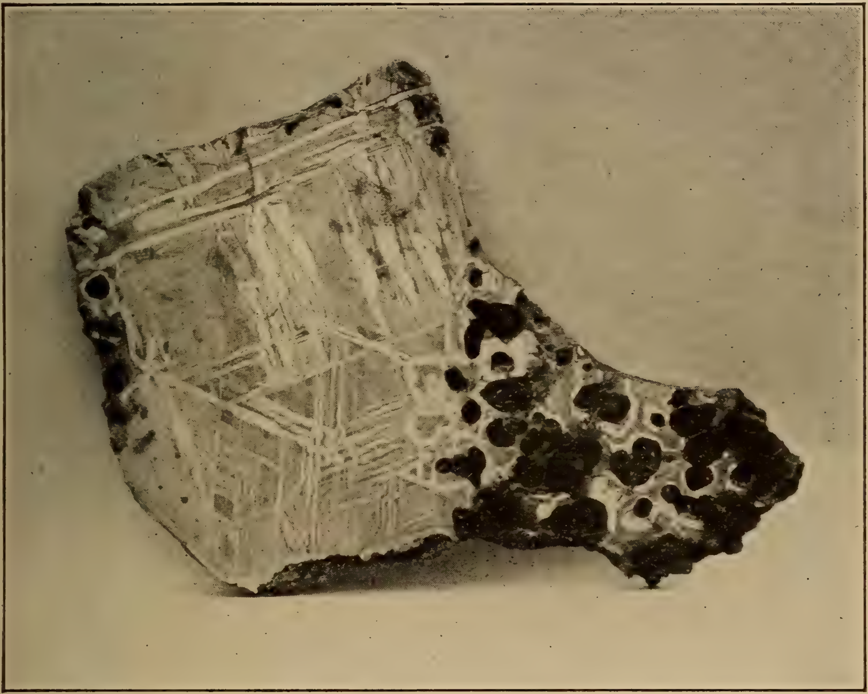

FIG. 11.—A partial section and a portion of the exterior of the Brenham (Haviland), Kans., meteorite, showing, in close relations, a coarse crystallization of nickel-iron and an intersegregation of metallic and non-metallic material, implying that the same general conditions affected both forms of aggregation. Ward-Coonley Collection. (From Ward.)

It remains to postulate a means of disruption and an agency of dispersion competent to give the disrupted fragments the erratic courses and the high velocities which meteorites possess, while at the same time the structural features, sometimes rather perishable, escape destruction by liquefaction or extreme pulverization.

Hypotheses of disruption and dispersion.—Any supposed explosion from an internal source is unsatisfactory because it is difficult to assign a sufficient and probable cause for an explosion capable of imparting a velocity of several miles per second, which would probably be required to disperse the fragments beyond the control of the system to which the body belonged, and because, if such sufficient explosion were realized, it must apparently wreck many of the peculiar meteoritic structures.

Collision with some other mass at a high velocity might be sufficient to disrupt the body and to drive its fragments away with the requisite velocity; but the imminent danger of liquefaction by the inevitable heat of the impact, or of extreme pulverization of the fragile material, raises doubt as to the adaptability of collision to the case of some of the stony meteorites of large size, and of the hydrocarbon meteorites, while it might answer well enough for minute meteorites. The relative rarity of collision also suggests a secondary place for it as an agency.

It has recently been suggested[1] that disruption by differential attraction might satisfy the requirements of the case, with perhaps some doubt as to adequate frequency. According to principles established by Roche, Maxwell and others, a small body passing within a certain distance (the Roche limit) of a larger dense body will be torn into fragments by differential attraction. The size of this sphere of disruption depends on the densities, cohesion, internal elasticities, and other factors of the two bodies. For incompressible fluids of the same density, Roche gives the limit of disruption as 2.44 times the radius of the large body. In most such bodies, internal elasticity probably exceeds cohesion and the sphere of disruption would be larger than this. The moon would probably expand with some violence if its gravity were suddenly removed by differential attraction. Fragmentation in this way would therefore be several times more probable than an actual collision. The fragmentation in this case is not minute nor violent.

A small body passing near a much larger body is liable to be thrown from its previous orbit into quite a new one. This has apparently happened to several comets through the influence of the planet Jupiter.

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[1] Chamberlin, On the Possible Function of Disruptive Approach in the Formation of Meteorites, Comets, and Nebulæ. Loc. cit.

If the orbit of the small body is such that it is caused to pass in front of the large body, say the planet Jupiter, its course will be diverted toward the sun, and its orbit shortened. If its course causes it to pass close behind the large body, its path will be diverted into a larger orbit. If a small body were to pass in this way sufficiently near to Jupiter, it might be thrown entirely out of the solar system.[1]

In these two sets of principles, there is a combination peculiarly fitted for the results required, for, by their joint action, a small body passing near a large body is liable to be disrupted into fragments, and, at the same time, to be thrown into an erratic course which may carry it entirely outside the system to which it belonged, and may give it a parabolic or hyperbolic course in stellar space. Fragmentation and dispersal by the differential attraction of very close approach escapes all of the adverse contingencies of liquefaction and pulverization incident to explosion or collision.

If the question be pushed a step farther to inquire how small bodies like the asteroids may be rendered specially subject to the requisite close approach, the answer may be found in the approach of suns, attended by such secondaries, to one another. For example, if the solar system were to pass even within five or six billion miles of a similar system, the orbits of the secondaries would be very greatly perturbed, and the balance between the centripetal and centrifugal accelerations, which now preserves the harmony of the system, would be so seriously disturbed that an intricate and prolonged series of changes would ensue. These are too complicated to be followed completely, but it is reasonable to believe that they might involve, sooner or later, the close approach of some of the smaller bodies to some of the larger. These smaller bodies in the solar system are numbered by hundreds, and the same may be suspected of other systems, and this largeness of number adds to the probabilities of some close approaches during a condition of general disturbance.

The solar system is probably not the most favorable selection for illustrating the contingencies of such disturbance, for it is a simple isolated system, with a single overpowering center that sways its attendants by a scarcely disputed control. It has swept through space undisturbed throughout the period of its present organization.

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[1] These principles have been worked out elaborately by H. A. Newton, Am. Jour. Sci. 16, 1878, pp. 165–179.

But there are many binary, triple, multiple, and clustered systems of suns which apparently divide the control of a common field, and this control may reasonably be supposed to involve approaches of sufficient nearness to one another to seriously perturb their outlying secondaries, and introduce disturbances ultimately involving disruptive approaches. The nebulous matter associated with some of these complex systems perhaps implies something of this kind.

Relations of meteorites to comets.—The hypothesis of disruption by differential attraction goes one step farther in postulating that the disrupted group of fragments may, in its earlier history, constitute a comet, since it is the general belief of astronomers that the comet's head is composed of a cluster of small bodies. The peculiar emanations which arise from a comet may perhaps be referred as plausibly to the occluded vapors and the radio-active substances of a shattered asteroid, as to any other recognizable source. The recent discoveries of the prevalence of radio-activity and allied phenomena render the cometic emanations less strange and exceptional than they once seemed.

The fragments of an asteroid, or other small body, disrupted in this manner would be given a rotatory movement by the differential attraction that produced them, and hence the resulting cluster of fragments should revolve about its center of gravity in a somewhat definite plane, but at the same time in more or less irregular and inharmonious paths as the result of the incidents of disruption, and this must render them subject to mutual disturbance, and to frictional and glancing collisions. If later conditions permitted a re-aggregation, a highly brecciated mass would result.

It is now accepted as highly probable that comets, particularly those that have short orbits and frequently return to the vicinity of the sun, are gradually dispersed by the latter's differential attraction. The mutual gravity of the cometic fragments being very small, the differential gravity of the sun, in its own neighborhood, becomes superior to it, and the members of the cometary cluster are drawn apart, and thenceforth revolve about the sun in their own individual orbits, irrespective of the other members. In other words, the swarm of meteoritic fragments that constitutes the comet's head passes into the planetesimal state by dispersion. In this we have an instance of that tendency of a swarm to pass into a planetesimal condition, to which allusion has heretofore been made.

These planetesimals constitute one variety of meteoroidal bodies, and it is to these that the brilliant August and September meteoritic showers are assigned. It has not been quite demonstrated that they are identical with the iron and stone meteorites above described, for they do not generally reach the earth, and it is not positively known that they have done so in any case, though one case of high probability is known; but their essential identity is extremely probable. In the fact that they have come to have individual orbits about the sun, and that these orbits are roughly parallel to one another, and that their velocities are of the same order, they do not represent the typical meteoritic condition, as heretofore defined. They rather illustrate the planetesimal phase of the meteoroidal condition.

The foregoing hypothesis of the origin of meteorites makes them but an incidental result of stellar and planetary action. Their genesis is wholly a secondary matter, and furnishes no ground for regarding meteorites as the parent material of great nebulæ or of stellar systems. The quantity of matter dispersed in this way is, by the terms of the hypothesis, limited to an extremely small part of the total mass of the system from which it is derived. It is therefore regarded rather as an incidental result of trivial importance than as a primary condition capable of generating great systems. This scattered matter is presumed to be picked up bit by bit by all the larger bodies, as is being done daily by the earth; and the maintenance of the supply requires only the disruption of small bodies to an extent equal to the trivial masses gathered in by the existing suns and planets. The exceedingly small amount of meteoritic material picked up by the earth is in harmony with this interpretation.

The hypothetical nature of this discussion of meteorites will be noted and due reserve in building other views upon it should be exercised, but the suggestions made in it may have some value in rounding out a consistent conception of the factors involved in the complex problem of which earth-genesis is a part, and may be helpful in distinguishing between competent generating factors and merely incidental by-products.

In conclusion, it may be remarked that the meteoritic condition seems most probably to be the product of incidental dispersion, and to be the source of merely incidental accretion by existing bodies, having neither great magnitude nor importance. It does not seem to represent a great generative method whereby stellar systems are evolved. Originated, by hypothesis, in dispersion, it is ever divergent in its own tendencies, passing into the gaseous state on the one hand, or into the planetesimal on the other, or, escaping these, it is depleted by contributing its constituents, one by one, to existing suns and planets.

III. The Planetesimal Hypothesis.[1]

Under the typical form of the planetesimal hypothesis, it is assumed that the parent nebula of the solar system was formed of innumerable small bodies, planetesimals, revolving about a central gaseous mass, much as do the planets today. The evolution of the system consisted in the aggregation of these innumerable small bodies into much fewer large ones; in other words, in a transition from a plantesimal to a planetary system. The hypothesis, therefore, postulates no fundamental change in the system of dynamics, after the nebula was once formed, but only an assemblage of the scattered material. The state of dispersion of the material at the outset and throughout, as now, was maintained *by orbital revolution*, or, more closely speaking, by the centrifugal acceleration arising from revolution. The planetesimal hypothesis by no means excludes gases from playing a part in the parent nebula, or in its evolution, any more than it denies their presence in the sun or the atmosphere to-day, but it assigns to gaseous action a subordinate place in the evolution of the planetary system after the planetesimal condition had become established.

Subvarieties of the hypothesis.

Under the broad general conception that planets grew from planetesimals, it is possible to entertain different views as to the particular origin of the planetesimal condition. That condition might be an outgrowth of a gaseous spheroid of the Laplacian type, or it might possibly be developed from a meteoritic state under certain conditions, or it might arise from the mode of dispersion to which the nebula itself was due. This last is taken as the type case.

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[1] This hypothesis has been gradually developed by the senior author of this work during the past decade, with the very important advice and aid of Dr. F. R. Moulton and other scientific friends. Partial expositions have been made before scientific societies at different times, and a somewhat extended statement appears in Year Book No. 3, Carnegie Institution, 1905, pp. 208–253, but this is its first full statement with illustrations. A statement from the standpoint of a mathematical astronomer and a master in celestial dynamics will be made by Dr. Moulton in his forthcoming work on astronomy.

Planetesimal condition arising from a gaseous spheroid.—If the parent nebula were a gaseous spheroid, as assumed by Laplace, and were to detach material from its equatorial belt, molecule by molecule, rather than by rings, these molecules would probably become planetesimals instead of members of a true gaseous body. It is not the thought that these molecules would be thrown off directly into planetesimal orbits, because their initial paths would probably be ellipses that would bring them back to the point of departure; but that, by certain classes of collisions while in these elliptical orbits, they would be diverted into orbits that would not bring them again into collision with the parent spheroid. It is not of sufficient importance to this discussion to explain in detail the process by which this would be accomplished, but the ingenious student will readily work it out for himself. There is reason to believe that this method would really be almost the only systematic one by which a gaseous spheroid of the Laplacian type would detach material from its equatorial belt.

But granting that this be not true, and that an earth-moon gaseous ring was formed, as assumed in the Laplacian hypothesis, computation shows that its attractive power at any one point on its surface would be very low. If the present earth were converted into a solid ring, occupying its present orbit, it would have a diameter of about twenty-five miles, with its present average density. Computation is scarcely necessary to show that the gravity of this ring, at any point on its surface, would be very feeble; and it is obvious that this gravity must be greater than the gravity on the surface of the same matter when dispersed in the form of a gas by intense heat. Now the application of the kinetic theory of gases to such a ring, under the postulated temperature, forces the conviction that the molecules would have been so driven apart by mutual collision that they would have become essentially independent of one another, each revolving in its individual orbit, with only rare and incidental collisions. In other words, they would have become planetesimals controlled by the central mass, and not a gaseous aggregate controlled by its own gravity. They would, therefore, not have been concentrated by direct attraction, on the principles controlling a cooling gaseous body, but would have been subject to accretion, one by one, in the modes presently to be described.

Planetesimal condition arising from the meteoritic.—Under certain circumstances, meteorites might possibly be assembled in such a way that they would come to revolve in concentric orbits about their common center of gravity, and thus assume a quasi-planetesimal condition, in contradistinction to that of a typical swarm of meteorites in which each is habitually drawn toward the center, collides, and rebounds after the fashion of gaseous molecules, as conceived by Lockyer and Darwin. The meteoroids that are formed by the dispersion of a comet, such as constitute the belts that give rise to the August and November meteoric showers, are probably in the planetesimal rather than the collision-rebound condition, and are becoming more and more scattered, and individually independent, as time goes on.

Planetesimal condition arising from original nebular dispersion.—The type view however, assumes that the parent nebula had a planetesimal organization from the outset. The conception is a rather radical departure from the gaseous conception of Laplace, and the meteoritic conception of Lockyer, so far as fundamental dynamics and mode of evolution are concerned. In the following sketch a rather special phase of this view will be adopted, partly for the sake of definiteness and such clearness as the complexity of the subject may permit, and partly for the following reasons:

(1) *It postulates that form of nebula which is by far the most common, the spiral;*

(2) *This form of nebula gives a spectrum consistent with a planetesimal constitution, if, indeed, it does not directly imply such a constitution;*

(3) *This form of nebula seems to possess the requisite mass-distributions and momenta;*

(4) *The special view of the origin of this form of nebula assumes only that which is liable to happen, is simple in its basal event, and is as mildly catastrophic as the genesis of a system can well be assumed to be.*

While this will be followed as the type view, let it be distinctly noted that the planetesimal doctrine of accretion does not stand or fall with this particular conception. As a first step in its deployment, let us turn to the heavens for such light as existing nebulæ may shed upon their own origin and constitution.

The characteristics of present nebulæ.

So far as their constitution is now revealed by the spectroscope, nebulæ fall into two general classes, the one characterized by bright spectral lines, the other by a continuous spectrum.

1. **Free-molecular nebulæ.**—The first are usually said to be gaseous, but this not a sufficiently accurate designation. The bright lines of the spectrum can only be affirmed to indicate that the matter of the nebulæ is in a *free-molecular* condition. They do not certainly indicate whether (1) the molecules are in the collisional relations of gaseous molecules, or (2) are scattered widely, like the stars of heaven, so that collisions are rare and incidental, or (3) are moving on radiating or on parallel lines, or (4) are pursuing concentric orbits and are thus planetesimal in dynamic character. For the purposes of this discussion, where dynamic distinctions are important, these nebulæ may be designated, with due reserve, simply as *free-molecular nebulæ.* They often have a greenish cast from the predominance of green lines in their spectra, and are conveniently styled green nebulæ. The bright spectral lines indicate the dominance of hydrogen, helium, and an otherwise unknown element, or elements, provisionally called nebulium. There are occasionally a few other non-metallic elements, but *metals have not been detected.* Their constitution, as now determined, does not, therefore, fit them for the parentage of our earth, in which metals abound and in which hydrogen and helium are subordinate elements, while nebulium is unknown. The possibility of transmutation into suitable elements cannot, to be sure, be safely denied in these days of revolutionary discoveries. The class includes the "planetary," the "stellar," the "ring," and most of the irregular nebulæ.

Almost identical with the spectra of these nebulæ are the spectra developed in an early phase of the declining stages of the new stars that occasionally flash forth with sudden brilliancy and soon die away to obscurity or extinction, continuous spectra sometimes marking the later stages. While the origin of these "*Novæ*" is unknown, the conjecture that they are due to collision or to explosion has been entertained, and this conception has also been extended to the free-molecular class of nebulæ. By remote and uncertain speculation under the stimulus of recent revolutionary discoveries in dissociation, the violence of their assigned origin may be in some way correlated with the extremely low molecular weights of their constitutent molecules and their apparently elementary condition. It is a further suggestive fact that the early spectra of these new stars and the green nebulæ are closely similar to those of the "helium stars" and the "hydrogen stars", which astronomers usually place in the first or 'earliest" group in evolutionary classifications of the stars. There is thus much of ground, therefore, for linking together in genetic studies these stars, the *Novæ,* and the helium-hydrogen-nebulium nebulæ, and for looking upon them provisionally, as primitive states. If our quest were the *genesis of stars,* these would seem to point the way, so far as anything does at present; but our quest is the genesis of the solar *family of planets,* in one of which our study centers; and the genesis of our earth is not necessarily and immediately connected with the genesis of stars. Nebulous bodies composed of helium, hydrogen, and the hypothetical nebulium might, for aught science dare now affirm, remotely evolve into material of the complex terrestrial type; but the speculation is rather too bold for prudent use as a basal factor in a conservative hypothesis.

The forms of the helium-hydrogen-nebulium nebulæ are scarcely more promising for planetary evolution, when their dynamical properties are considered. While observation has, as yet, determined almost nothing as to their internal movements, their forms do not encourage the belief that they would, under known laws, evolve into a system characterized by the peculiar distribution of mass and momentum which the solar system presents. For the present, therefore, these nebulæ may be passed by in a search for the immediate genesis of the earth.

2. **Aggregate-molecular (planetesimal?) nebulæ.**—The other class of nebulæ give continuous spectra, and are conveniently styled white nebulæ. The continuous spectrum is interpreted to mean that their chief luminous material is in a liquid or solid state, or perhaps better, that the molecules are in an *aggregated* state, in distinction from the free state of the previous class. As the liquid condition is limited to a rather narrow range of temperature, and as this range is very different for different materials, it is improbable that any large portion of a nebula is in this state, and the whole may be conveniently treated as though solid, but in a finely divided condition. This last qualification seems necessary, for the volume of these nebulæ is often very great,

and yet they appear to intercept but little light, and give no signs of great attractive power.

The dominant form of these nebulæ is the *spiral*, as determined by the late Professor Keeler,[1] and this form particularly characterizes the smaller nebulæ recently brought to knowledge by improved instruments and manipulative skill. These newly discovered nebulæ are estimated to number at least ten times the whole number previously known. From the superior number of spiral nebulæ it is a safe inference that their peculiar forms represent some prevalent process in celestial dynamics. That is, in itself, a reason why research should turn to them by preference for the origin of the present solar system.

Nothing is yet positively known of *the motions* of the parts of these spirals, for time enough has not yet elapsed since they were first sharply photographed to permit the requisite comparisons. Inferences from their remarkable forms are the only present resource. The accompanying photographic illustrations of some of the larger and more distinct forms will permit independent judgment as to the validity of these inferences (Figs. 12 to 21). To us their peculiar forms seem to imply that the spirals sprang from *a combined outward and rotatory movement*. The outward movement may have been already checked by the gravity of the central mass, and the rotatory motion be dominant at present, but their forms seem still to bear the impress of an outward movement. If the outward movement has ceased, or when it

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[1] The profoundly lamented death of Professor Keeler, just as he was beginning to reap the rich fruits of his skill and patience in nebular investigations, gives historical value to his latest statement of results, published about two months before his death.

"1. Many thousands of unrecorded nebulæ exist in the sky. A conservative estimate places the number within reach of the Crossley reflector at about 120,000. The number of nebulæ in our catalogues is but a small fraction of this.

"2. These nebulæ exhibit all gradations of apparent size from the great nebula in *Andromeda* down to an object which is hardly distinguishable from a faint star-disk.

"3. Most of these nebulæ have a spiral structure. . . .

"While I must leave to others an estimate of the importance of these conclusions, it seems to me that they have a very direct bearing on many, if not all, questions concerning the cosmogony. If, for example, the spiral is the form normally assumed by a contracting nebulous mass, the idea at once suggests itself that the solar system has been evolved from a spiral nebula, while the photographs show that the spiral nebula is not, as a rule, characterized by the simplicity attributed to the contracting mass in the nebular hypothesis. This is a question which has already been taken up by Professor Chamberlin and Mr. Moulton of the University of Chicago."—Astrophys. Jour., June 1900, pp. 347, 348.

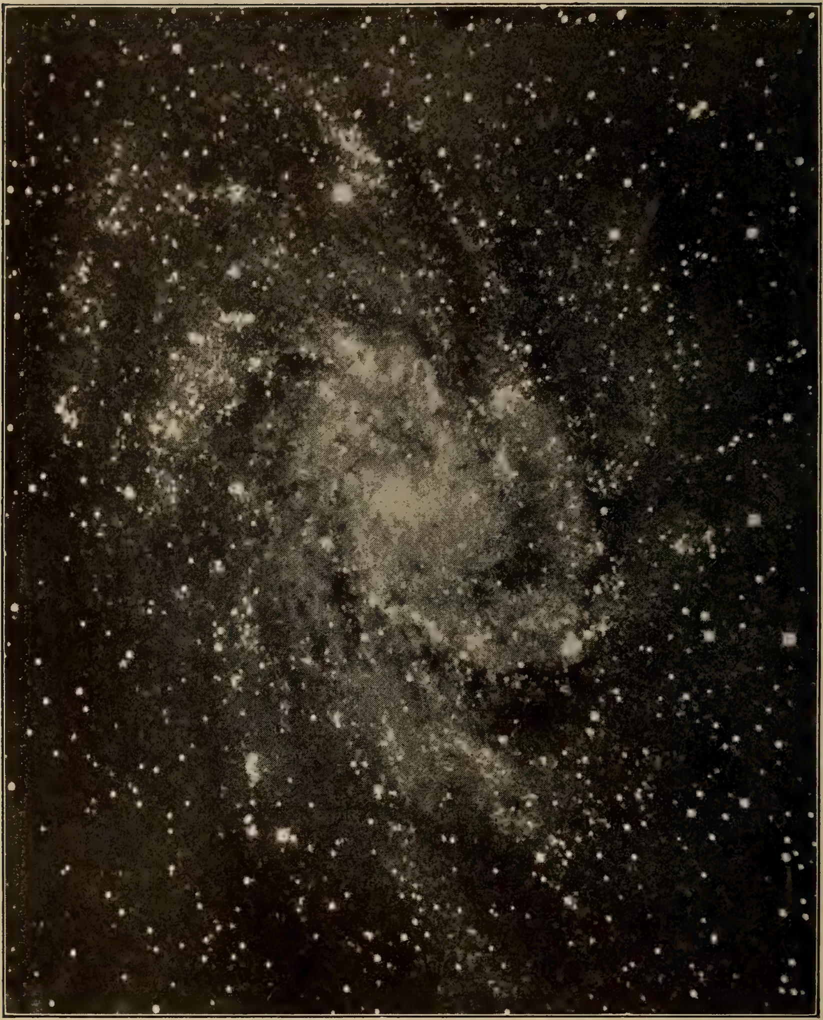

Fig. 12.—A very large, highly dispersed nebula, Messier 33, in the Triangle, in which the knots are very pronounced and the nebulous haze is irregular and flocculent. It is interpreted as young, because the arms are not greatly coiled and the nebulous haze has not become generally distributed. A succession of expulsive impulses seems to be indicated. Judged by the luminosity, the amount of matter in the nucleus is relatively small, and so the difference in the motions of the outer and inner parts is much less than in a system of the solar type, and the evolution is very slow. The distance is unknown, and hence the dimensions are unknown, but they are probably much greater than those of the solar system. There is much uncertainty in judging of the mass by the luminosity, for some of the matter may have little luminosity and some may not be luminous at all. The central and denser portions are likely to be relatively more luminous than the dispersed portions. (Photo. by Ritchey, Yerkes Observatory.)

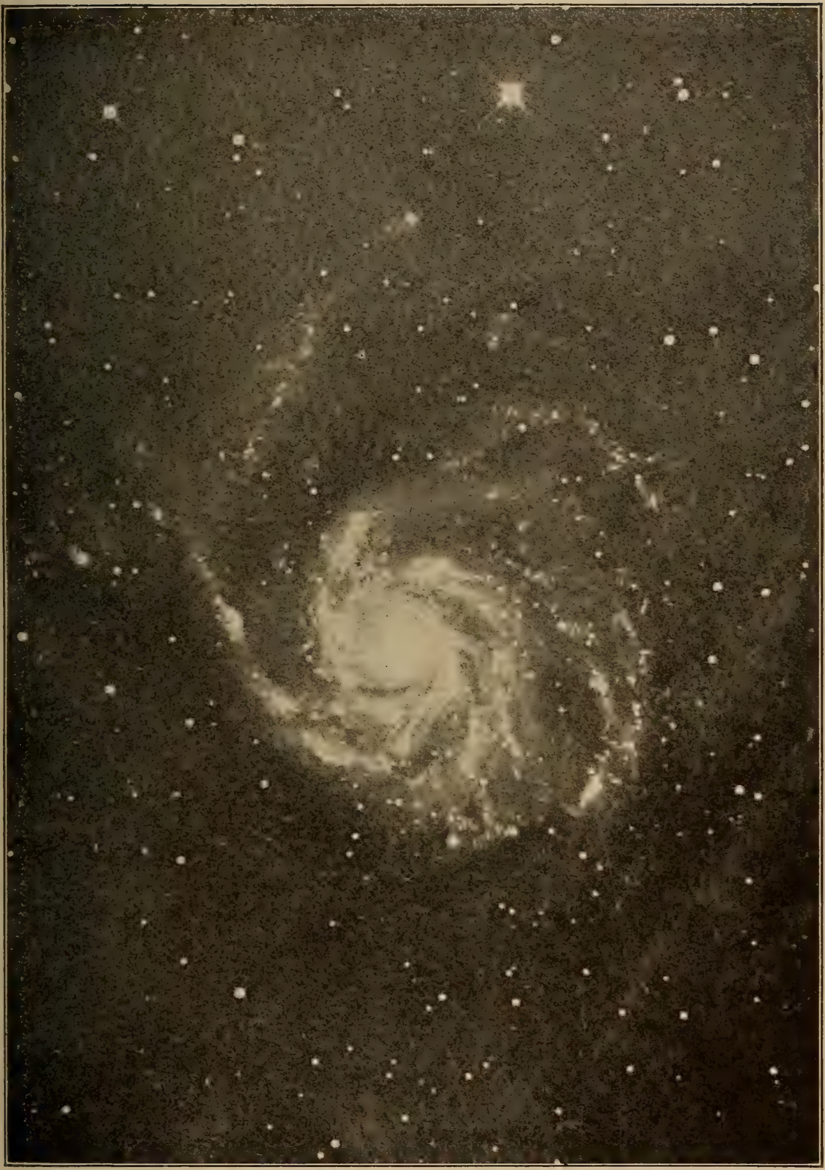

FIG. 13.—A spiral nebula in Ursa Major, Messier 101. The arms are much divided, which is assigned to a succession of expulsions at successive stages of approach. (Photo. by Ritchey, Yerkes Observatory.)

ceases, the rotatory movement must tend to wrap the spiral up more and more closely[1] and symmetrically, because the revolutions of the inner parts must be more rapid than those of the outer parts. The forms that seem to be the more mature appear to betray this, for the inner parts are coiled more closely and symmetrically than the outer parts. This is notable in Figs. 13 and 14. In the remarkable nebula in Canes Venatici (Fig. 14) there are curved streamers, like the tails of comets, stretching outward from some of the knots in the arms. If these are indeed streamers driven outward from the knots and

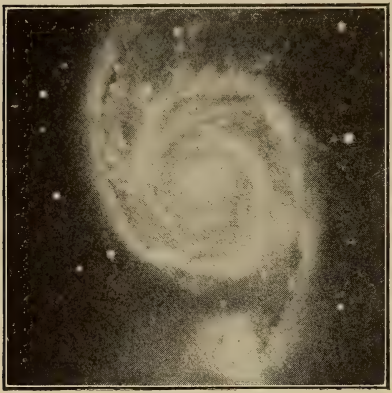

Fig. 14.

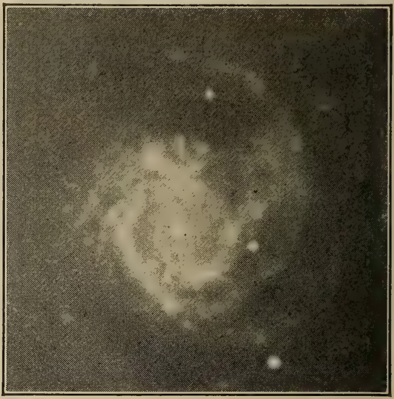

Fig. 15.

Fig. 14.—A brilliant spiral nebula in Canes Venatici, Messier 51. The exposure was long and has given relative exaggeration to the fainter parts. The nucleus is apparently dense and relatively massive; the coiling is pronounced and rather symmetrical in the inner parts, but departs from symmetry in the outer parts. A second nucleus is attached to the extremity of one arm. If this be interpreted as the representation of the disturbing star, it should perhaps be regarded as made of colder, heavier material, much less subject to expulsive elasticity, and hence less dispersed, and only slightly affected by rotating influences. A notable feature is the comet-like streamers of some of the knots and denser portions. If these are true streamers, curved by motion, they imply an active rotation and strengthen the similar inference drawn from the coiled condition. The system is perhaps to be interpreted as young, but as having advanced rapidly in its rotatory evolution because of its massive nucleus. (Photo. by Ritchey, Yerkes Observatory.)

Fig. 15.—A spiral nebula (Messier 61) in which the central mass is sharply defined, the immediately surrounding portion diffuse and hazy, while the outlying portion retains its spiral distribution. The middle of the outer portion appears to contain most of the outlying matter, the distribution somewhat resembling that in the solar system. The dimensions here are presumptively much greater than those of the solar nebula, but this is not certainly known. (Photo. from Lick Observatory.)

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[1] This does not mean that the matter is drawn toward the center, but merely that the arms are stretched and more closely coiled.

curved by motion, as in the case of comets' tails, they testify very definitely to a rotatory movement.

A notable and seemingly very significant feature of these nebulæ is the presence of *two dominant arms* that arise from diametrically opposite sides of the nucleus, and curve concentrically away. No single-arm spiral of the watch-spring type has been found. There are often more than two arms in the outer part, and there is much irregularly dispersed matter, but even in the more scattered forms the dominance of two arms is discernible.

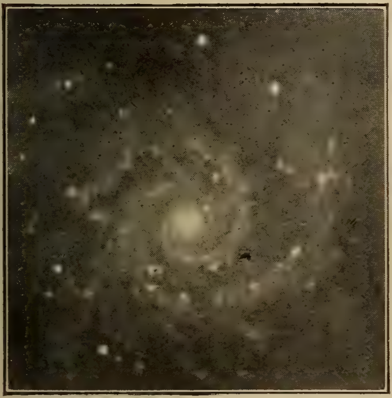

FIG. 16.

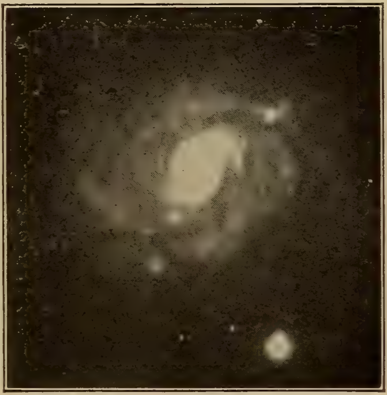

FIG. 17.

FIG. 16.—A typical spiral nebula in Piscium, Messier 74, with very symmetrical arms, pronounced nucleus and knots, and a relatively limited amount of nebulous haze. (Photo. from Lick Observatory.)

FIG. 17.—A suggestive nebula in Ceti, Messier 77, in which the proportions between the apparent masses of the central and the outlying parts is somewhat analogous to those assigned the solar nebula; so also are the proportions between the knots and the nebulous haze, and the number of the knots is also similar, but the volume of the central portion is disproportionately large. (Photo. from Lick Observatory.)

A second feature of note is the presence of numerous *nebulous knots* or partial concentrations on the arms, and more or less outside them. So, also, the more diffuse nebulous matter is unequally distributed, and in some of the forms, regarded as youngest, dark spots and lines emphasize the irregularity (see Fig. 12).

All these features go to show that these forms are controlled, not by the support of part on part, as in a continuous body, or in a mass of gas, or even in a definite swarm of quasi-gaseous meteorites, but by some system of combined kinetic energy and gravity which *permits inde-*

pendence of parts. It is, therefore, conceived that the innumerable solid or liquid particles which the continuous spectrum implies, revolve about the common center of gravity as though they were planetoidal bodies. If this were certainly known to be the case, these might be well called *planetesimal nebulæ.*

It is clear from the tenuity of these nebulæ, as seen from the side of the spiral, that they are thin and disk-like, and this is directly shown to be so in the case illustrated in Fig. 18, which is seen obliquely. The slender ellipse shown in Fig. 19 probably represents a spiral seen edgewise, but this is not certain. In their disk-like shapes, these nebulæ conform to the mode of distribution of matter in the solar system. Within the area of their disks also, the distribution is irregular as it is in the solar system—a fact too much overlooked by reason of our predilection for symmetry, under the influence of the symmetrical Laplacian conception.

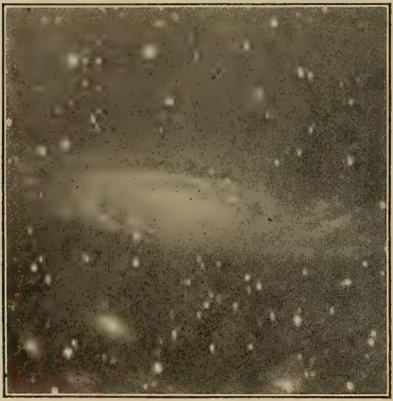

Fig. 18.

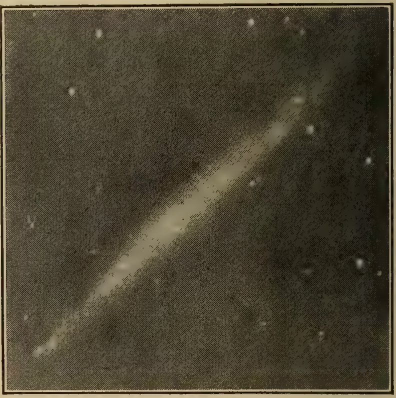

Fig. 19.

Fig. 18.—A spiral nebula in Pegasi (HI 53), seen obliquely, showing the disk-like form. (Photo. from Lick Observatory.)

Fig. 19.—An elliptical nebula (HV 41), interpreted uncertainly as a possible spiral seen from a point in its own plane. (Photo. from Lick Observatory.)

If these nebulæ are composed of minute aggregates of matter revolving as planetesimals about the nebular centers, *the momentum of the outer parts is necessarily high* in proportion to that of the inner portions, and in this essential particular they meet the most stubborn of the difficulties that confront the Laplacian hypothesis.

All of the spiral nebulæ of our illustrations have dimensions that vastly transcend those of the solar system, and they cannot be taken as precise examples of the solar evolution. Because of these vast dimensions and of the probable feebleness of control of the central mass, which often appears to be itself quite tenuous, a rapid motion cannot well be assigned to the arms. Seen from the immense distances at which the nebulæ seem to be placed—no parallax having been as yet detected—changes of position must necessarily be slow in revealing themselves to observation. It is to be hoped, however, that the present rapid progress in the perfection of instruments and of skill will soon

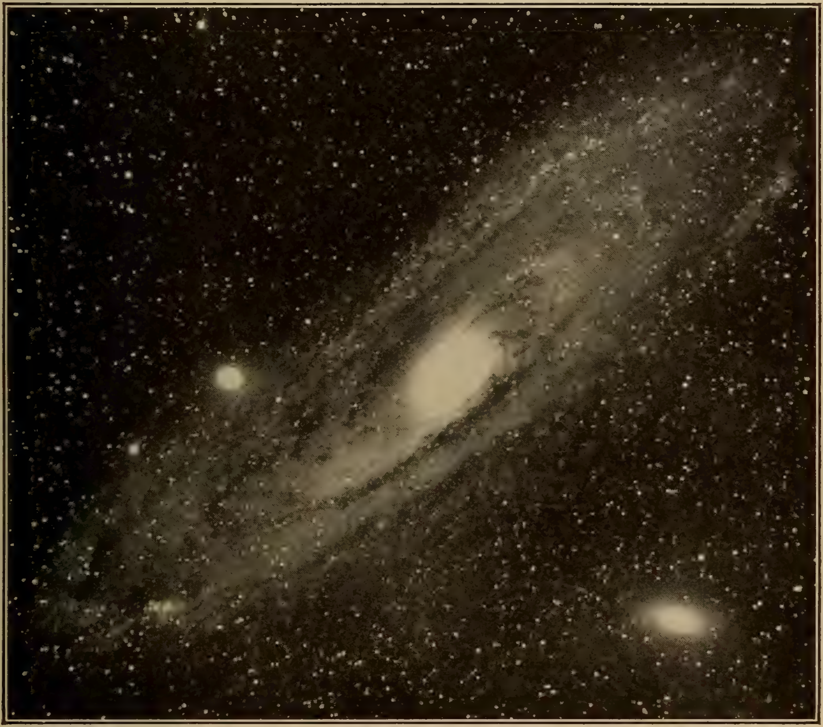

FIG. 20.—The great nebula in Andromeda, seen, apparently, obliquely; the greatest of the spiral nebulæ. The nucleus is highly preponderant and spheroidal; the knots are less pronounced than in the preceding, and nebulous haze is more abundant relatively. The spectrum is continuous, with some dark lines, implying that the central nucleus is akin to the sun. No parallax has been determined, but the distance is inferred to be great and the dimensions immense, as many small stars *appear* to be this side the nebula. This nebula has sometimes been suspected to be in reality a stellar system outside our own. Two smaller spheroidal nebulæ are shown which may or may not be connected genetically with the great one. (Photo. by Ritchey, Yerkes Observatory.)

bring within the reach of successful study some of the smaller spiral nebulæ that represent more nearly, in mass and proportions, the solar system, and that some of these will be found sufficiently near to permit an early determination of their motions.

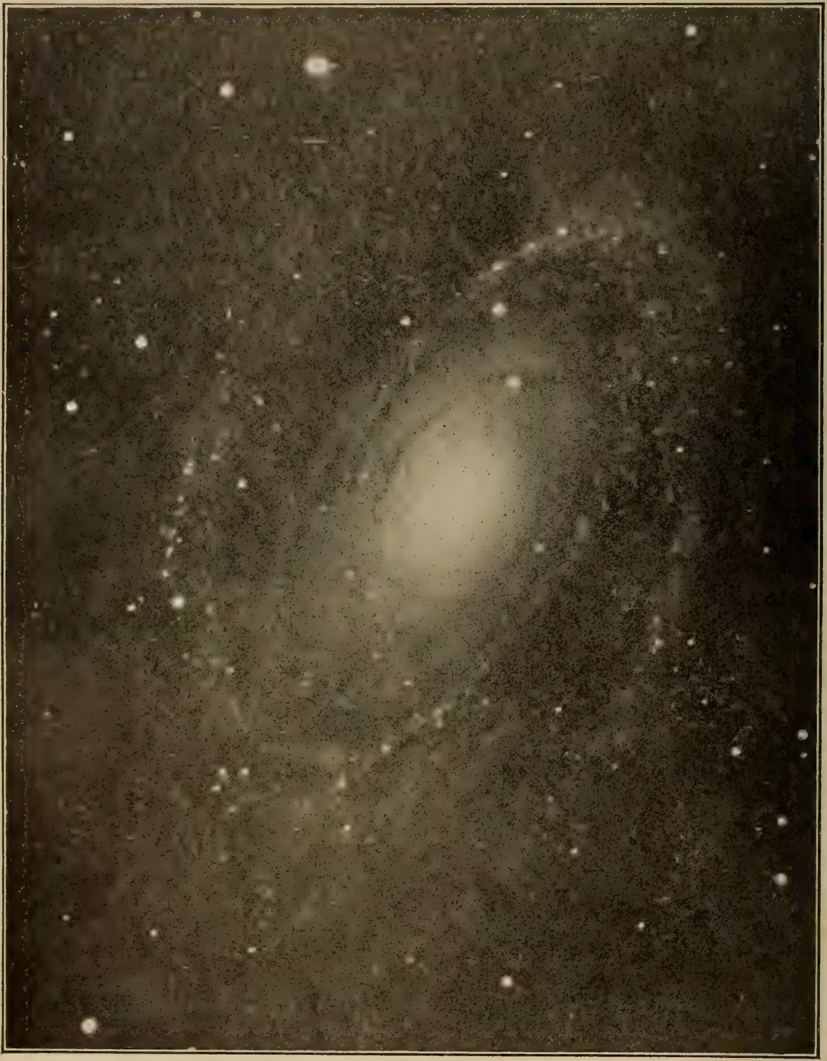

Fig. 21.—A spiral nebula in Ursa Major, Messier 18, showing a large dominant central mass, with symmetrical arms, well coiled. Form and proportions not unlike those assigned to the parent solar nebula. Interpreted as somewhat advanced in evolution. (Photo. from Lick Observatory.)

While awaiting, for how long we cannot tell, such positive determination, it may contribute to clearness of view, even if it shall fail to be an anticipation of the real fact, to definitely picture the possible origin of the supposed nebula that grew into the present solar system.

The hypothetical origin of the solar nebula.

An implied ancestral system.—The inference that a spiral nebula is formed by a combined outward and rotatory movement implies a preëxisting body that embraced the whole mass. In harmony with this, an ancestral solar system is postulated—a system perhaps in no essential respect different from the present one. Our hypothesis does not, therefore, concern itself with the primary origin of the sun, or of the stars, or with the ulterior questions of cosmic evolution. It confines itself to a supposed episode of the sun's history, in which the present family of planets had its origin, and in the initiation of which a possible previous family may have been dispersed; but no affirmation is made relative to the last point. With some partiality perhaps, this episode may be regarded as geologic, since it specially concerns the birth of the planet of which alone we have intimate knowledge.

The question of adequacy of energy.—To this conception of an ancestral sun, with an undefined antecedent history as a star, question will arise at once as to a sufficiency of energy for the sun's maintenance through such a prolonged history. It has been strongly urged during the past half-century, by very eminent physicists, that the resources of energy assignable for the maintenance of the sun's heat and light could, at best, be barely sufficient for the geological and biological demands of the earth's known history, even when these are most conservatively estimated. How much less then can they be sufficient for an antecedent history of unknown duration! This objection is based on the assumption that the sun's heat and light are derived *almost wholly* from self-compression, as urged by Helmholtz. That self-compression is a potent source of heat is not questioned, but the Helmholtzian theory takes no account of sub-molecular and sub-atomic sources of energy. The transcendent potency of these sources of energy has been for some time suspected,[1] and is now being revealed by refined physical research. The extraordinary energies displayed by radio-active substances are doubtless but an initial demonstration of immeasurable energies resident in other forms of matter and in the constitution of the sidereal system, and competent for its maintenance for unassignable periods. It does not appear, therefore, in the light of recent revelations in physics, or recent discoveries in the constitution of the stars and the stellar system, that there is any sufficient reason for setting narrow limits to the life of the sun. It seems more in accord with recent advances in knowledge to place the compressional theory of the sun's heat in the category of the earlier chemical and meteoritic theories, as true and contributory, but as only partial and inadequate. The one thing, perhaps, above all other things, which the progress of research is bringing into recognition is the immensity of the energy of the universe, of which energy only a small fraction is usually apparent to us, doubtless because it is *chiefly in a state of equilibrium*, and only becomes sensible when its equilibrium is disturbed.

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[1] The following was written in 1899 before experimental demonstration had been reached: "Without questioning its correctness, is it safe to assume that the Helmholtzian hypothesis of the heat of the sun is a complete theory? Is present knowledge

There seem to be no sufficient grounds, therefore, for hesitating to assume an ancestral solar system, the center of which was the parent of the present sun. This involves the further quite reasonable assump-

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relative to the behavior of matter under such extraordinary conditions as obtain in the interior of the sun sufficiently exhaustive to warrant the assertion that no unrecognized sources of heat reside there? What the internal constitution of the atoms may be is yet an open question. It is not improbable that they are complex organizations, and the seats of enormous energies. Certainly, no careful chemist would affirm either that the atoms are really elementary, or that there may not be locked up in them energies of the first order of magnitude. No cautious chemist would probably venture to assert that the component atomecules, to use a convenient phrase, may not have energies of rotation, revolution, position, and be otherwise comparable in kind and proportion to those of a planetary system. Nor would he probably feel prepared to affirm or deny that the extraordinary conditions which reside in the center of the sun may not set free a portion of this energy. The Helmholtzian theory takes no cognizance of latent and occluded energies of an atomic or ultra-atomic nature. A ton of ice and a ton of water at a like distance from the center of the system are accounted equivalents, though they differ notably in the total sum of their energies. The familiar latent and chemical energies are, to be sure, negligible quantities compared with the enormous resources that reside in gravitation. But is it quite safe to assume that this is true of the unknown energies wrapped up in the internal constitution of the atoms? Are we quite sure we have yet probed the bottom of the sources of energy and are able to measure even roughly its sum total?"—On Lord Kelvin's Address on the Age of the Earth as an Abode Fitted for Life. T. C Chamberlin, Science, Vol. IX, June 30, and Vol. X, July 7, 1899.

tion that the sidereal system has had a very prolonged history, and that the ancestral sun played its part in it as the solar system does now.

The contingencies of stellar collision.—There are probably at least 100,000,000 suns in the present sidereal galaxy, and these are moving, so far as now determined, in various directions and at various velocities, much like the molecules of an exceedingly tenuous gas. Besides these suns, there is possibly even a larger number of dark bodies associated with them as extinct suns, planets, planetoids, and satellites. It would be strange, therefore, if there were not occasional collisions, especially in the more crowded portions, as in the Milky Way, however rare these might be relatively. It is in or near the Milky Way that new stars appear, and also there that the free-molecular nebulæ chiefly abound. This coincidence of distribution obviously does not, of itself, carry so broad a conclusion as that the new stars and the free-molecular nebulæ necessarily arise from collision; but the contingency of collision, when such a multitude of bodies are moving in such diverse ways, can scarcely be questioned, notwithstanding the vast distances involved and the consequent smallness of the contingency for a given body within a limited time. But to the phenomena of collision no appeal is here made, except as a part of a consistent conception of the whole group of associated phenomena.

The contingencies of close approach.—If there are contingencies of actual collision between stars, there must be much larger possibilities of their *close approach* to one another and to dark bodies. Celestial bodies possess velocities inherited from past states, and velocities due to the existing attraction of other bodies, so that close approach is assignable in part to the crossing of predetermined paths, and in part to the mutual attraction of the great bodies themselves. The contingencies of collision and of close approach arising from these two factors follow different laws. Considering inherited motions alone, the contingencies of collision are greatest when the velocities are highest and the bodies thickest. The contingencies of close approach by mutual gravity are greatest when previously acquired velocities are least and conflicting attractions are fewest and feeblest. It is obvious that as the inherited velocities approach infinity, collision approaches infinite frequency, while gravitational deflection approaches the infinitesimal. On the other hand, if inherited velocities were reduced to zero, gravitation would draw a finite group of stars directly together. When both factors are present, *relative freedom from collision and disruptive approach* lies between the two extremes. A numerical inquiry [1] leads to the interesting conclusion that most of the existing velocities lie near that happy medium that gives fewest catastrophes, from which the inference is drawn that *a selective process has removed most of the bodies of dangerously high and dangerously low velocities, and has left those possessed of the relatively safe intermediate velocities.*[2]

If all stellar motions are like the known motions, and if the known stars constitute a system by themselves, a uniform velocity cannot be maintained in all parts of the stars' courses, nor can like velocities prevail in all portions of the system. The velocities must be highest, on the average, when a star is traversing the interior of the group, and the contingencies that attend high velocities must be there resident. The inherited velocities must be presumed to be lowest on the outer borders of the system, where the constituent bodies reach the limit of their outward excursions and turn back, under the gravity of the system, to again traverse it. This at least seems the most tenable conception of the movements of the members of the stellar system, considered as a finite group of bodies possessed of the known motions and controlled by the known forces. The alternative conception of an infinite extension of stars is beyond treatment here. On the outer borders, therefore, mutual attraction is assumed to be relatively more potential than in the central portions. But, as some residual motion derived from previous excursions is even there retained, and as a part of this is almost inevitably tangential, *close approaches* rather than collisions are the disturbing contingencies indicated.

In this outer portion also, the paths assigned the stars are *more nearly parallel,* because all are approximately parallel to the surface of the stellar sphere at their turning-points, and hence such inherited energies as the bodies possess oppose less resistance to the approach of the bodies to one another, for it is only when the motions are in opposite or transverse directions that their kinetic energies resist gravitative approach.

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[1] Made by the senior author in coöperation with F. R. Moulton and C. E. Siebenthal.

[2] There are, however, a number of stars with great enough velocities to carry them beyond the visible system, even after allowing liberally for dark bodies (Moulton).

In harmony with this conception is the fact that the known spiral nebulæ are distributed on the sides of the supposed stellar disk or flat spheroid of which the Milky Way is the assigned equatorial girdle. If spiral nebulæ occur on the outer border of the Milky Way, as our view seems to imply that they should, they are doubtless beyond the limits of distinct vision.

Whatever may be the value of this particular view of the causes of close approach, it is a consistent, if not necessary, assumption that, in a multitudinous stellar system characterized by diverse rates of motion in diverse directions, close approaches of suns to one another are contingencies likely to be realized in fact.

The special consequences of close approach.—Our present sun shoots out protuberances to heights of many thousands of miles, at velocities ranging up to 300 miles and more per second. If it were not for the retarding influence of the immense solar atmosphere, some of these outshoots would doubtless project portions of themselves to the outer limits of the present system, and perhaps, in some cases, quite beyond it, for the observed velocities sometimes closely approach the controlling limit of the sun's gravity, if they do not actually reach it.[1] This illustrates the enormous explosive elasticity resident in the sun's interior. The expansive potency of this prodigious elasticity is held in restraint by the equally prodigious power of the sun's gravity.

If, with these potent forces thus nearly balanced, the sun closely approaches another sun, or body of like magnitude, possibly one several times the mass of the sun, since the sun is regarded as a small star, the gravity which restrains this enormous elastic power will be *reduced along the line of mutual attraction*, on the principle made familiar in the tides. At the same time the pressure transverse to this line of relief will be increased. Such localized relief and intensified pressure must bring into action corresponding portions of the sun's elastic potency, resulting in protuberances of corresponding mass and high velocity.

Dynamic considerations seem to make it clear that the sun might even thus be wholly disrupted, if the body to which it approached were much superior to it in mass and the approach were very close. Roche long ago demonstrated that the differential attraction of a large body upon a smaller one revolving about it, was competent to disrupt it at an appreciable distance, as previously stated (p. 34). In a body whose elasticity nearly matches its gravity, it is not necessary that the Roche limit should be actually invaded before disruptive phenomena of a high order of intensity and magnitude would take place. A more distant approach would suffice.

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[1] A body falling from infinity to the sun's surface, and thus acquiring the maximum velocity which the sun's attraction can give to it, would strike the sun's surface at 382 miles per second, which is technically known as "the velocity from infinity," or the "parabolic velocity," since a body shot from the sun with this velocity would take a parabolic path and never return. This, therefore, represents the maximum power of control of the sun, and the velocity of some protuberances is nearly equal to it.

Exceptional protuberances developed on opposite sides by close approach.—According to the well-known tidal principle, these exceptional protuberances would rise from opposite sides, and herein lies the assigned explanation of the prevalence of two diametrically opposite arms in the spiral nebulæ.

The demands on protuberant action not severe. — The present planets and their satellites, all together, amount to about one seven-hundredth part of the mass of the system. Simply to supply the required planetary matter, the protuberances need include but this small fraction of the ancestral sun; but some considerable part of the projected matter must probably have been gathered back into the sun, and some part may possibly have been projected beyond the control of the system. Making allowances for both these factors, the proportion of the sun's mass necessarily involved in the protuberances is still very small. Apparently one or two per cent. of the sun's mass would amply suffice.

The acquisition of rotatory motion.—The protuberances, by hypothesis, would be thrust out as the sun and the passing star were swinging about their common center of gravity in curves more or less sharp, and at velocities more or less prodigious, according to their relative distances. That protuberance which was shot from the sun toward the star would be drawn forward by the star in the direction of its movement, with a power inversely proportional to the square of the distance. The protuberance shot in the opposite direction would be attracted by the star also, but owing to its greater and constantly increasing distance, in a very greatly less degree, in accordance with the same law. The sun at an intermediate distance would be attracted in an intermediate degree. With reference to the sun, therefore, the two protuberances would move in opposite directions, and their motions relative to it would be revolutionary. To follow out even approximately the actual motions of the sun and the protuberances in a given case of this kind is extremely difficult and laborious. It is obvious, furthermore, that in any given instance a succession of protuberances following one another at different stages of approach must probably have taken place, and hence the formation of a nebula presents a series of such extremely difficult problems. Dr. Moulton has worked out the selected case of two opposite protuberances, in which the mass of the passing star is assumed to be equal to that of the sun, and the protuberances are assumed to be shot out to twice the star's perihelion distance (Fig. 22). It is further obvious upon consideration that the number of possible cases that might arise from the varying ratios of the masses and from the varying distances of their approach, is very large, and that immense labor is involved in covering the whole ground and finding out what cases are applicable to the problem of the solar nebula, but in the course of the series now being worked out under the direction of Dr. Moulton, it is hoped that a close approximation to the solar nebula may be found, a hope which seems to be warranted by the results thus far obtained. Analytical considerations have seemed to show that if the disturbing star were equal to or more massive than the sun, and were to pass very near to it, a large portion of the sun would be dispersed with great velocity, and the resulting nebulæ would probably resemble those immensely expanded ones which are chiefly represented in the foregoing illustrations. A more distant approach in which the protuberances are small relative to the mass of the sun seems to be more in consonance with the demands of the solar problem. It will be

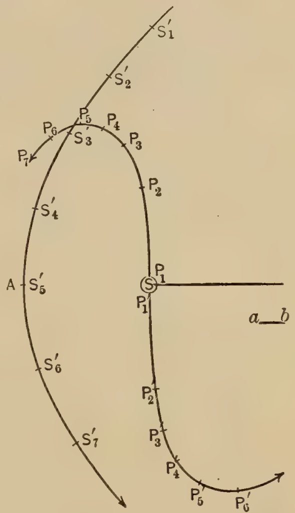

Fig. 22.—Diagram illustrating the courses pursued by particles, P and P', shot out from the sun, S, on opposite sides under the disturbing influence of a passing star, S', when at the position S_1'. The successive positions of the disturbing star are indicated by S_1', S_2' . . . S_7', assumed at successive time-intervals. When S' was at the position S_1', the particles P and P' were shot out from S with velocities such that if not disturbed they would have reached to distances twice AS. $P_2 \ldots P_7$ and $P_2' \ldots P_7'$ are the successive positions assumed by these particles at the successive times. a–b is the acceleration at unit distance. (After F. R. Moulton.)

observed that the curves in Fig. 22 are of the general order which the case requires.

The distribution of specific gravities.—The distal portions of the protuberances would obviously be formed from the superficial portions of the sun, while the later portions of the ejections forming the proximal parts of the arms would doubtless come mainly from lower depths, and hence probably contain more molecules of high specific gravity. In this seems to lie a better basis for explaining the extraordinary lightness of the outer planets, and the high specific gravities of the inner ones, than in the separation, from the extreme equatorial surface of a gaseous spheroid, of successive rings whose mass never equaled the one-thousandth part of the original nebula.

Successive partial outbursts.—It seems consistent with the conditions of the case to assume that the protuberances would consist of a succession of more or less irregular outbursts, as the ancestral sun, in its swift whirl around the controlling star, was more and more affected by the latter's differential attraction; and hence the protuberances would be directed in somewhat changing courses, and would be pulsatory in character, resulting in rather irregular and somewhat divided arms, and in a knotty distribution of the ejected matter along the arms. These knots must probably be more or less rotatory from inequalities of projection.

The result a spiral nebula.—It is thus conceived that a spiral nebula, having two dominant arms on opposite sides, each knotty from irregular pulsations, and rotatory, the knots probably also rotatory, and attended by subordinate knots and whirls, together with a general scattering of the larger part of the mass in irregular nebulous form, would arise from the simple event of a close approach.

Theoretical diagram of the solar nebula.—On the basis of the foregoing considerations, there is herewith presented a theoretical restoration of the solar nebula (Fig. 23). The purpose of this is to give a definite conception of the favored phase of the planetesimal hypothesis—not to enforce its correctness or acceptance. On the contrary, the frank concreteness it gives to the conception facilitates criticism, and invites modification by future study.

The passage of the molecules from the free to the aggregated state.—The ejected matter, at the outset, must have been in the free molecular state, since by the terms of the hypothesis it arose from a gaseous body; but the vast dispersion and the enormous surface exposed doubtless quickly reduced the more refractory portions to the liquid and solid state, attended by some degree of aggregation into small accretions; hence the continuous spectrum which this class of nebulæ present.

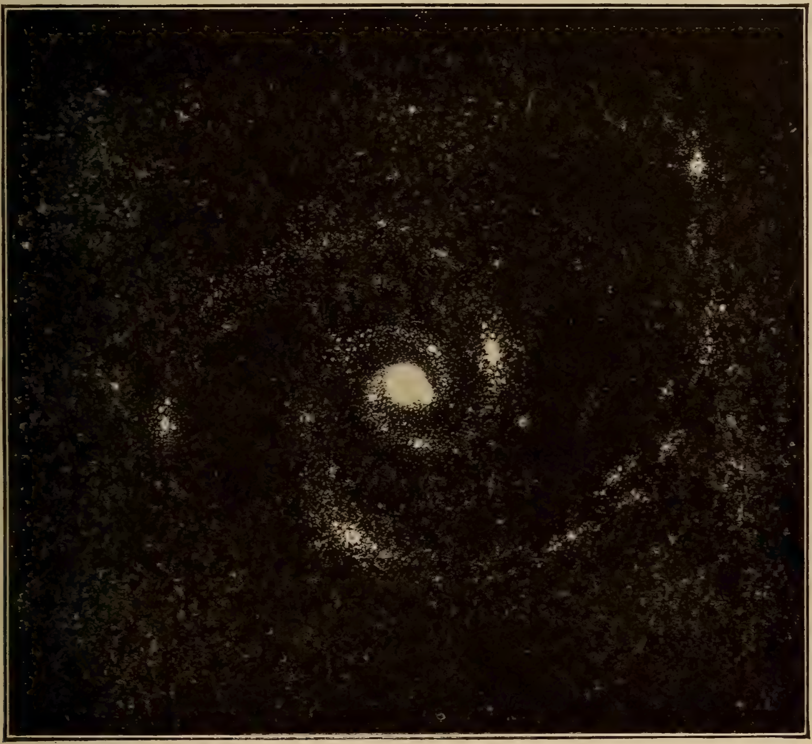

FIG. 23.—Theoretical restoration of the parent nebula of the solar system. The nuclei of the several planets may be indentified by their distances from the center. The dimensions of the inner parts are made disproportionately large.

Nebular luminescence.—The problem of the luminescence of nebulæ is confessedly a puzzling one. There is little ground for assigning general incandescence to matter so obviously scattered and tenuous, and possessed of such enormous radiating surface. The assignment of the light to collisions of meteorites, as has been done by Lockyer, encounters both dynamic and spectroscopic difficulties. The recent discoveries of the luminescent properties of radio-active matter, and of its power to awaken luminescence in other matter, offers hope of a solution. The fact that these properties are not necessarily dependent on heat greatly relieves the stress of the problem. Whatever of radio-active material there might be in the matter dispersed into nebulous form would, by such dispersion, be set free for action, and whatever other matter was subject to its excitation would also be set free to receive the exciting influence.

The solution of the problem may, however, lie along electrical lines. At present it seems more probable that the luminescence arises from some agency that acts at low temperatures than that it is dependent on heat, and hence objections to a planetesimal organization on the ground of low temperature cannot have much force.

The assigned nebular origin not vital.—Whether the particular mode of origin of the spiral nebula just sketched be true or not, is not vital to the planetesimal hypothesis. It is offered as a definite genetic picture and as a contribution to the natural demand for a conceivable mode of genesis. It is only vital to the planetesimal hypothesis, as here developed, that the scattered nebular material shall revolve around the central mass in elliptical orbits, and this may perhaps be sufficiently implied by the forms of the spiral nebulæ without raising the question of their origin. It is true that their forms have been interpreted as implying streams of *in-running* matter following spiral courses, but a system of dynamics, on known principles and consistent with known conditions, has never been worked out for such a process, so far as we are aware, and it is not evident how it could be.

As a basis for following onward the evolution, two simple assumptions only are necessary, (1) that the nebular matter of the spiral is in a finely divided solid or liquid condition, as the continuous spectrum implies, and (2) that the particles of this scattered material revolve in elliptical orbits about the central mass.

The evolution of the nebula into planets.

The three essential factors.—The knotty spiral form of the nebula gives ground for recognizing three factors as the chief participants in the evolution into a planetary system, (1) the central mass (to become the sun), (2) the knots (to become the nuclei of the planets), and (3) the diffuse nebulous matter (to be added to the nuclei to form the planets or to be added to the sun). Fitting the conception to the special case of the solar nebula, the present distribution of mass and energy warrant the assumptions that (1) the central mass was overwhelmingly large, (2) the knots were quite irregular in size and very unequal in distance from the center, and (3) the nebulous part was small relative to the central mass, and probably large relative to the knots. Reasons for the last conclusion will be given later.

The attractive powers of the knots and their limitations.—It is assumed that the masses of matter in the knots were sufficiently large to hold themselves together in spite of the differential attraction of the central mass; otherwise they would soon have been scattered. They seem to have successfully maintained themselves in nebulæ that appear to have undergone some notable degree of evolution, as for example the knots shown near the large central nucleus in Fig. 13.

On the other hand, it is presumed that the gravity of the more tenuous nebular matter was insufficient to aggregate it directly, in the presence of the central attraction, for this portion seems to show a progressive tendency to a more general diffusion, as may be seen by comparing the cloudy flocculent distribution of the nebulous matter in Fig. 12, whose form implies that it is young in evolution, with the more diffuse distribution in Figs. 15, 17, 18, and 21, whose central coilings imply more advanced states of evolution. The planetesimals of this diffuse nebulous portion are, therefore, assumed to be controlled essentially by the gravitation of the main mass, and to revolve in individual orbits about it.

The irregularity of the forms of the knots seems to imply that their organization is also planetesimal, though the larger ones may be able to hold gases also. The direction of revolution of these knots is supposed to be usually the same as that of the rotation of the nebula as a whole, but subject to local and special influences that might lead to important variations.

The knots the planetary nuclei.—The knots of the solar nebula are regarded as the nuclei about which gathered the planetesimals to form the future planets; not that all such nuclei necessarily retained their independence and grew to planets, but that no planet probably developed except from such a nucleus. The figures already presented (Figs. 12–21) show clusters of knots and aggregates of irregular form susceptible of development into complex planetary systems, such as the large planets and their families of satellites. The earth-moon system is assigned to a couplet of companion nuclei of quite unequal sizes.

The sizes of the nuclear masses.—If the present planets have grown from these nebular nuclei, the greatness of their growth is measured by the smallness of the primitive nuclear masses. The amount of such accretion is a matter of geologic interest, for it is fundamentally related to many dynamical questions of the earth's later history. There are two considerations that bear upon the size of the original nuclei.

1. There is a certain inherent and necessary limitation to the size of scattered or tenuous bodies in the presence of more massive bodies. The principle involved is one of vital importance in the study of planetary evolution. Within the field of the effective attraction of a dominant body like the sun, or the ancestral nebular center, small bodies exercise differential gravitative control over a limited sphere only, known, technically, as the "sphere of activity." This sphere for the earth, with its *present mass*, reaches out about 620,000 miles.[1] If the earth has grown at all, its primitive sphere of control must have been smaller than this. The earth nucleus could, therefore, only have embraced such matter as lay within this limited sphere. If the original knot could be supposed to have extended beyond this limit, the outlying portion would have been drawn away by the solar mass into independent planetesimals, and must have been gathered in, if it became a part of the earth, by some other means than direct attraction. The moon controls, as against the attraction of the earth at its present distance, a sphere whose radius is about 25,000 miles; and considerably less than 25,000 miles as against the joint attraction of the earth and sun. Its primitive nucleus, if it has grown at all, was confined to smaller dimensions. Attenuated nuclei of indefinite size cannot, therefore, be supposed to maintain themselves permanently in the fields of attraction dominated by larger bodies. Bodies of gas, subject to the dispersive effects of their own molecular velocities, in addition to the competitive gravity of dominant bodies, have still narrower limits, and below a certain mass are inevitably dispersed. In such a system as ours, gases must, for the most part, either join themselves to the dominant bodies or be scattered into molecular planetesimals. None of the smaller knots of the solar nebula could probably have been gaseous in any large measure. Gases were probably attached to and occluded in the aggregated or solid planetesimals, and

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[1] "The Spheres of Activity of the Planets," Moulton, Pop. Astro., No. 66, p. 4.

may have been held in a free gaseous state in the interiors of the larger nuclei. The sun is of course presumed to have been gaseous throughout the evolution.

2. Quite a definite indication of the size of the nuclei of the planets may perhaps be deduced from the very remarkable fact that Phobos, the inner satellite of Mars, revolves around the planet in *less than one-third* of the time of the planet's rotation, and from the analogous fact that the little bodies which make up the inner part of the inner ring of Saturn revolve about that planet in a little more than *one-half* the time of the planet's rotation.[1] These are exceedingly troublesome facts from the view-point of the Laplacian hypothesis, for under it the contraction of these planets, after they had shed their secondaries, should have greatly accelerated their rotations, and these should have become much shorter than the revolutions of the secondaries. Before Moulton's citation of the second case, an attempt was made to explain the case of Phobos by a supposed tidal retardation of the planet's rotation, but the Saturnian case appears to render this explanation incompetent.[2]

Under the hypothesis of growth from a nucleus by the addition of planetesimals, the rotations of the planets were dependent largely on the special phases of the impacts of the infalling planetesimals, and no necessary relations between the rotation of a planet and the revolution of its satellite are assignable. But if this be neglected, and the rotation-period of the planetary nucleus be assumed to have been originally the same as the revolution-period of the satellites' nucleus, *the growth of the mass of the planet must have drawn the satellite nearer to itself, and shortened the time of its revolution.*

If the whole of the periodic difference between Mars and Phobos be due to this cause, the growth of the nucleus of Mars is deducible from it. Under this view, the matter of the rings of Saturn may have been satellite nuclei at the outset, and have been drawn within the Roche limit by the growth of Saturn, and then disintegrated by tidal action and distributed into the ring form. All other satellites should, under this view, have been drawn towards their primaries during the growth of the latter, and this may be a not unimportant factor in their evolutionary history.

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[1] For a discussion of these phenomena, see "An Attempt to Test the Nebular Hypothesis by an Appeal to the Laws of Mechanics," Moulton, Astrophys. Jour., 1900, p. 109.

[2] See Moulton's discussion, loc. cit., pp. 109, 110.

The concurrent bearings of these two considerations are quite in harmony with what might be gathered independently from a comparison of the apparent amounts of matter in the nebular knots with the amounts in the nebular haze. It will, therefore, be assumed, in our further study, that the nuclei constituted only a small portion of the mass of the grown planets. The fraction was probably larger *proportionately* for the small planets than for the large ones, for the power of growth probably rose with increased mass in geometrical ratio. In the case of the asteroids and satellites the growth may not have been large.

The mode of accretion.

The nature of the planetesimal motions.—The gathering of the planetesimals to the nuclei to form the planets is assigned essentially to conjunctions in the course of their orbital motions, not to simple gravitation, except as gravitation was the fundamental cause of the orbital motions. The nature of the primary motions is, therefore, a first consideration. The combination of outward and rotatory motion to which the formation of the nebula is assigned, while giving a spiral form to the whole, at the outset, is believed to have given to each individual planetesimal *an elliptical orbit about the common center.* If, recurring to our hypothesis of the origin of the spiral, the outward and the tangential impulses had been duly balanced, circular orbits would have resulted; but neither theory nor observation make it probable that this was often the case. The inevitable inequalities of the two components should give ellipses varying in eccentricity with every variation in their relations. As, however, both the outward and the rotatory components sprang from the same source—the gravitative disturbance induced by the approach to a massive star—there is reason to think that they would not be extremely unequal, and that the resulting eccentricities, though large, would not be excessive. This view is in accord with the forms of the spiral nebulæ. These do not present spirally symmetrical configurations of the strictly circuloid type, but broadly elliptical ones, with irregular elements. The development of the present almost circular configuration of the solar system out of such a broadly elliptical, somewhat irregular, spiral configuration involves an evolution in the direction of circularity and symmetry, in the course of the aggregation of the scattered matter. The method will be presently indicated.

The part played by ellipticity of orbit.—The ellipticity of the orbits is the very factor that furnishes the assigned agency of aggregation, and of this progressive evolution towards circularity and symmetry. In the initial stages, the ellipses of the nuclei and of the innumerable planetesimals were, by reason of their common origin, rudely concentric. They were, to be sure, more or less discordant in form and in attitude from the effects of unequal projection, of differential expansion of the solar matter when set free by projection, and of the collisions of the constituent planetesimals; but all of this was subordinate to a general concentric arrangement of the elliptical paths. Under the laws of celestial mechanics, these paths must have been constantly modified by the different attractions of the different portions of the nebula. The axes of the orbits must have shifted, the attitudes of their orbital planes must have varied, and their eccentricities must have been modified. It will suffice to consider the shifting of the major axes of the orbits, technically "the motion of the line of apsides," as that is the most vital factor in the process of aggregation.

So long as the major axes of the orbits were essentially parallel to one another, as *A* and *B* in Fig. 24, the bodies would remain apart and aggregation be prevented; but when they became shifted differentially to the positions *A′* and *B′*, the orbits would touch, and conjunction be possible, if the orbital planes were appropriately related to one another.

The shifting of the lines of apsides is in constant progress in the present system, and must of necessity take place in any such system, as the laws of celestial mechanics require it. The shifting is differential and subject to various perturbations, involving alternate movement forward and backward, but the average result is an advance.[1] At present the line of apsides of quickest revolution is that of Saturn, which completes its circuit in 67,000 years, roundly speaking, while that of Neptune requires 540,000 years, and that of the earth a little more than 100,000 years.[2] In the course of time, the major axis of each orbit is thrown athwart that of its neighbors, and whenever the

[1] Celestial Mechanics, Moulton, p. 245.

[2] Young's General Astronomy, p. 313.

longer axis of the smaller orbit is equal to the shorter axis of the larger orbit, and the planes of the orbits are properly related, collision is rendered contingent. Actual collision is dependent, of course, upon the bodies reaching the crossing of their paths at the same time. The planes of the planetary orbits now lie near to one another and are presumed always to have done so. These planes, though not necessarily

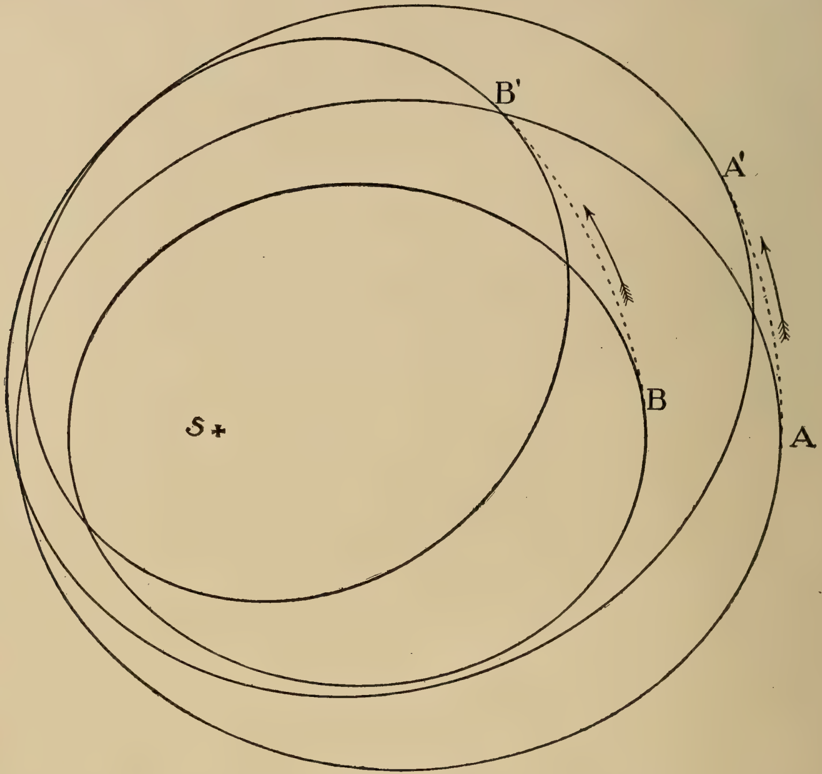

Fig. 24.—Diagram of a smaller orbit, *B*, lying within and parallel to a larger orbit, *A*, both having a common focus, *S*; the absence of the conditions of conjunction is obvious so long as they retain this relation even approximately, but when they shift differentially to the positions *A′* and *B′*, conjunction is made possible, if the planes are properly related. If the orbit *A* were to shift the more rapidly, the effect would be the same.

the orbits, intersect one another, and the lines of intersection are shifting so that in time all assignable intersections are realized. Under these conditions, the mechanics of such a system furnish the requisite contingencies for collisions between the planetesimals and the nuclei, if sufficient time be granted.

The collisions of isolated planetesimals with one another may be neglected, for it is uncertain whether the planetesimals would rebound from one another or would unite; probably the former when they were highly elastic, and the latter when inelastic; and probably much would also depend on their velocities and their modes of impact; but in any case, the result would only affect the size and number of the planetesimals. The important consideration is the impact of the isolated planetesimals upon the planetary nuclei. In this case the usual result must apparently be the capture of the planetesimals by the nuclei, and with each capture, the power of further capture would be augmented.

The evolution of circularity.—When two bodies in concentric elliptical orbits unite, their conjoined mass must move in an orbit that is intermediate between the two previous orbits, and this new orbit, in all cases investigated, is less eccentric than one of the previous orbits, and may be less eccentric than both, as illustrated in Figs. 25 and 26. While a mathematical demonstration that this is universally true is possible, the illustrations suffice to show that it holds for most normal cases falling within the problem in hand. It follows that the union of an indefinite number of orbits progressively reduces the resulting orbit toward circularity. In application, there arises the obvious corollary that the planets which have grown most have, in general, lost most of their primitive eccentricity and those that have grown least most nearly represent the original eccentricity. The significant application of this to the planets of the solar system will appear later.

The time involved.—When the slowness of the motion of the line of apsides, and the only partial coincidence of the planes of the orbits, at any one time, are duly considered, it is evident that the contingencies of collision for the entire number of planetesimals will be spread over a protracted period, and that collisions can succeed one another rapidly only as the immensity of the possible number insures this. Individually, the chances of collision are remote and infrequent; but as the numbers involved at the outset were prodigious, the impacts upon a given nucleus in a given time may have been numerous. In the nature of the case, the impacts must have declined in frequency after the greater number of planetesimals had been gathered into the nucleus.

The bearings of the rate of infall on temperature.—The rate of accretion is a matter of radical geologic importance; indeed, it is, in some measure, the most critical feature of the whole nebular problem; for the rate of accretion determines whether the average temperature on the surface of the growing body will be high or low. The surface temperature is not determined by the total heat produced by the collisions, but by *the heat produced in a given time* which, in turn, is determined by *the frequency and force of the collisions on a given area.* If the succession of collisions on a given square mile is not rapid enough to generate heat beyond the concurrent radiation from the square mile, a high average temperature for the whole cannot be reached, however great the sum total of heat generated in the course of time. It

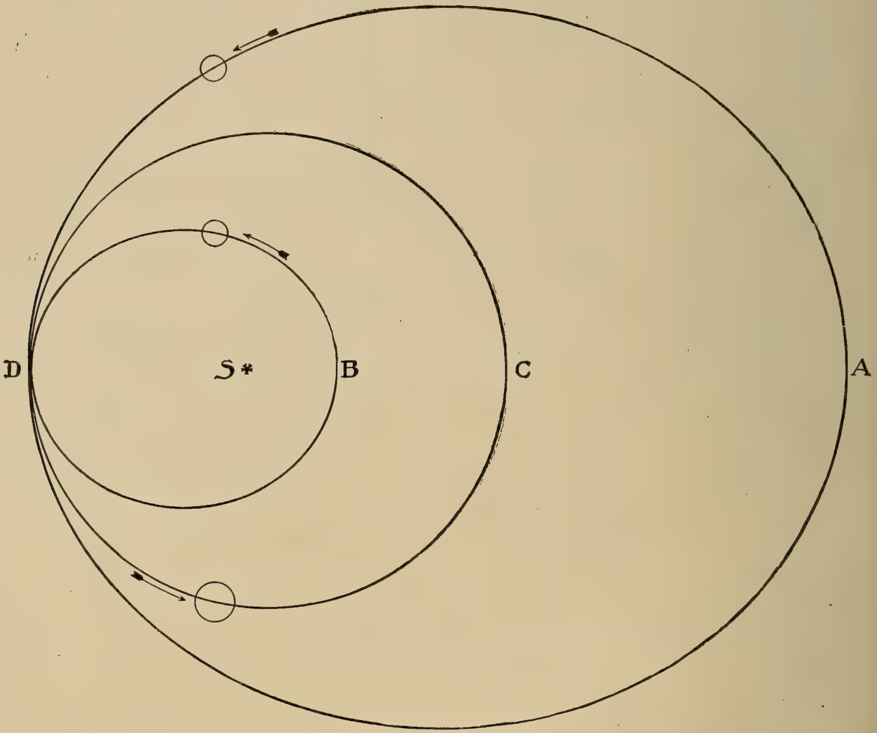

Fig. 25.—Diagram to illustrate the tendency toward circularity when the orbits of the uniting bodies have concentric positions. The two bodies revolving in the orbits *A* and *B*, and uniting at *D*, necessarily take an intermediate orbit, *C*, with an obvious advance toward circularity. In less simple and symmetrical cases, the result is less obvious, but it would be of the same order in all cases involved in the problem in hand.

is to be noted that the heat generated after a solid nucleus was developed must have been superficial, and hence readily radiated away. While the nuclei remained assemblages of small bodies, perhaps gaseous in part in the larger ones, planetesimals from without may have penetrated to the interior, and there developed heat not so readily lost. But this state is only assignable to the early stages of growth.

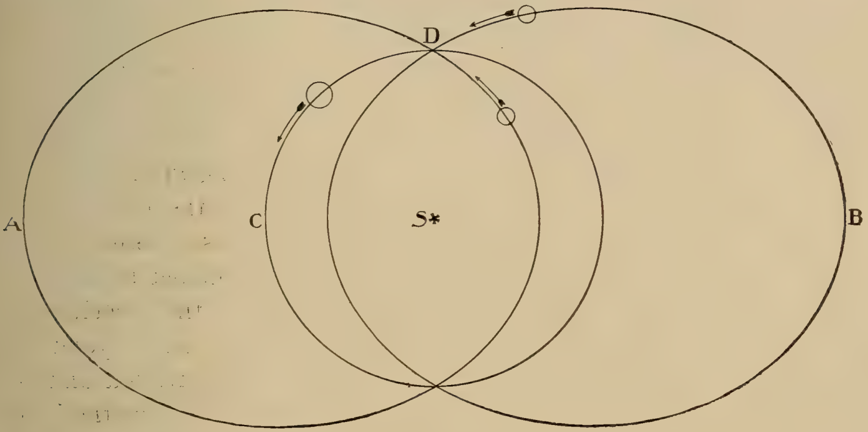

Fig. 26.—Diagram to illustrate the evolution of circularity where the orbits of the uniting bodies are as far as possible from having concentric positions. The bodies in the orbits *A* and *B*, meeting and uniting at *D*, necessarily take an intermediate orbit *C*, which is obviously more circular than either. In less symmetrical cases, the tendency would be of the same order.

The collisions all overtakes.—A further consideration bearing upon the critical subject of temperature is the manner of collision. Since all the planetesimals and planetary nuclei were revolving *in the same direction* about the solar mass, the collisions were all overtakes, and could have been violent only to the extent of their differences of orbital velocities, modified by their mutual attractions. Since their orbits were elliptical, their velocities varied considerably in different portions of their paths, and hence overtake collisions of considerable velocity were possible. These velocities were, however, of a much lower order than the average velocities of meteoritic collisions. Many of the overtakes must obviously have been due to differences of velocity barely sufficient to bring about an overtake. When the average mildness of impact is considered, in connection with the intervals between impacts at a given spot, the conviction can scarcely be avoided that *the surface temperature would not necessarily have been high.* It seems probable that it would have been moderate throughout most of the period of aggregation, and certainly so in the declining stages of infall.

The bearing of the mode of accretion on the direction of planetary rotation.—We have now reached a point where the hypothesis can be tested. It happens to be a point where all hypotheses of this class have been supposed to be fatally at fault. The crucial feature lies in *the direction of rotation* which would result from the gathering-in of matter in this way. At the same time, the bearing of the discussion broadens, for this vital question of direction of rotation attaches to all forms of aggregation of independent bodies moving in orbits about the common center of a system. For example, if the evolution of the solar system be supposed to start with a gaseous spheroid of the Laplacian type, and to proceed in the manner postulated by Laplace until the planetary rings were formed, and if then the velocities of the molecules, resulting from mutual impact, carried them beyond the gravitative control of the rings so that they were scattered and revolved independently around the central mass, the hypothesis of their aggregation would be as much subject to the test of rotation as the special hypothesis now under consideration. So, too, if, instead of forming definite rings, the molecules were separated from the supposed gaseous spheroid, one by one, as seems more probable than separation by rings, their aggregation is equally open to the supposedly fatal weakness. So indeed is the concentration of any kind of an assemblage of discrete matter in which the individual molecules or aggregates revolve independently.

The lion in the way—and he appears to have turned back many a pilgrim—is as follows: In a ring revolving *as a unit*, as the Laplacian rings are supposed to have done, the outer part moves faster than the inner part; and so, if a planetary ring parts at its weakest point and gathers into a globe about the center of its cross-section, it will rotate *forward*, as shown in Fig. 27. If, on the other hand, the particles of the ring revolve *independently*, the inner ones must move faster than the outer ones, and if they collect about the middle part, it has been held that the rotation must be *retrograde*, as illustrated in Fig. 28.[1]

By way of exception, to meet the singular cases of Uranus and Neptune, it has been suggested that if the matter of the planetary rings, revolving as units, happened to collect about some point other than the center of the cross-section, the foregoing conclusions would not hold, but if the matter were drawn together by gravity simply, as usually supposed under the Laplacian hypothesis, it is not evident why it should not collect about the middle part.

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[1] For ampler statements of this difficulty, see Faye, "Sur l'Origine du Monde," pp. 165, 270–281, 1896. Also Young's General Astronomy, pp. 518–20.

Now as matter of fact, the six inner planets and their satellites rotate *forward.* The satellites of Uranus revolve backward in a plane inclined 82.2° to the ecliptic; those of Neptune also revolve backward, in a plane inclined 34.5° to the ecliptic. The rotations of these planets themselves have not been determined. These exceptional inclinations and revolutions have been interpreted as very oblique or partially overturned revolutions. Accepting the foregoing premises, the prevalence of direct rotation has been regarded as strongly confirmatory of an origin from gaseous rings rotating as units, and as strongly adverse to accretion from bodies revolving independently. The force of this line of reasoning has apparently been felt to be so strong as to be essentially fatal to the latter conception. It, therefore, requires critical consideration.

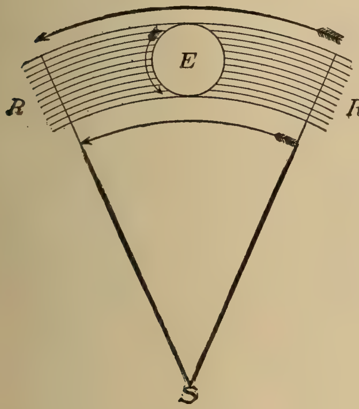

Fig. 27.

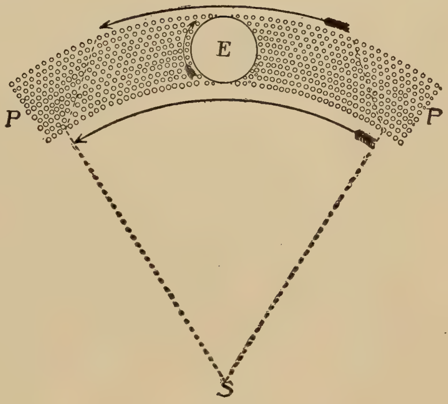

Fig. 28.

Fig. 27.—*RR* represents a ring of gas moving as a unit and hence the outer portion the faster. If converted into a spheroid, *E*, centrally located, the rotation is forward, as shown by the arrow.

Fig. 28.—*PP* represents a belt of planetesimals revolving concentrically about the center, *S*. If these collect about the central point of the belt into a spheroid, *E*, by the enlargement of the inner orbits or the reduction of the outer ones, the concentric arrangement remaining, the rotation will be retrograde, as shown by the arrow.

The reasoning is good *for the special case cited*, that of a symmetrical ring of perfectly circular form, in which the inner bodies, in uniting with the outer ones, are supposed to strike their inner sides. To bring about this delicate adjustment systematically, the orbits must remain closely concentric, and the inner ones must be enlarged, or the outer ones be reduced, so that they will approach concentrically to within the sum of the semi-diameters of the bodies to be united. If planetesimals were arranged in strictly circular concentric orbits, and were separated from one another at the distances the case requires, the mechanics by which they could be brought into this special mode of collision consecutively is not evident, and has not been explicitly pointed out. It is certain that their union into a spheroid would not be, by any means, the simple direct and rapid process usually assumed.[1] On consideration it will be seen that the postulated case is a very special and quite artificial one, for all the present planetary orbits are *elliptical,* and are by no means strictly concentric.

It becomes evident, on studious consideration, that in any case which could probably arise from any actual antecedents, the planetesimals *must have had elliptical orbits;* for even if they arose from a gaseous ring of the Laplacian type, the rebounds of the molecules, as they collided and separated, must have given rise to non-concentric elliptical orbits. Even in this case the eccentricities must probably have been many million times the sum of the semi-diameters of the particles. In the case of planetesimals derived from a spiral nebula, the orbits are necessarily assigned very notable eccentricities. In all these cases, the most available mode of aggregation, if not the sole practicable one, lies *in the crossing of the orbits* brought about by the constant shifting of their major axes, as already set forth.

Now a planetesimal in a smaller elliptical orbit can come into contact with a planetary nucleus in a larger orbit *only* when a more or less *ap*helion portion of its orbit coincides with a more or less *peri*helion portion of the larger orbit of the nucleus, and a planetesimal in a larger orbit can come into contact with a planetary nucleus in a smaller orbit only when a more or less *peri*helion portion of its orbit coincides with a more or less *ap*helion portion of the nucleus orbit, as shown in Fig. 29. To illustrate by a pronounced case, a planetesimal, P, in the orbit A (Fig.

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[1] This has been discussed mathematically by Moulton—"An Attempt to Test the Nebular Hypothesis by an Appeal to the Laws of Dynamics," Astrophys. Jour. Vol. XI, pp. 115-126, 1900.

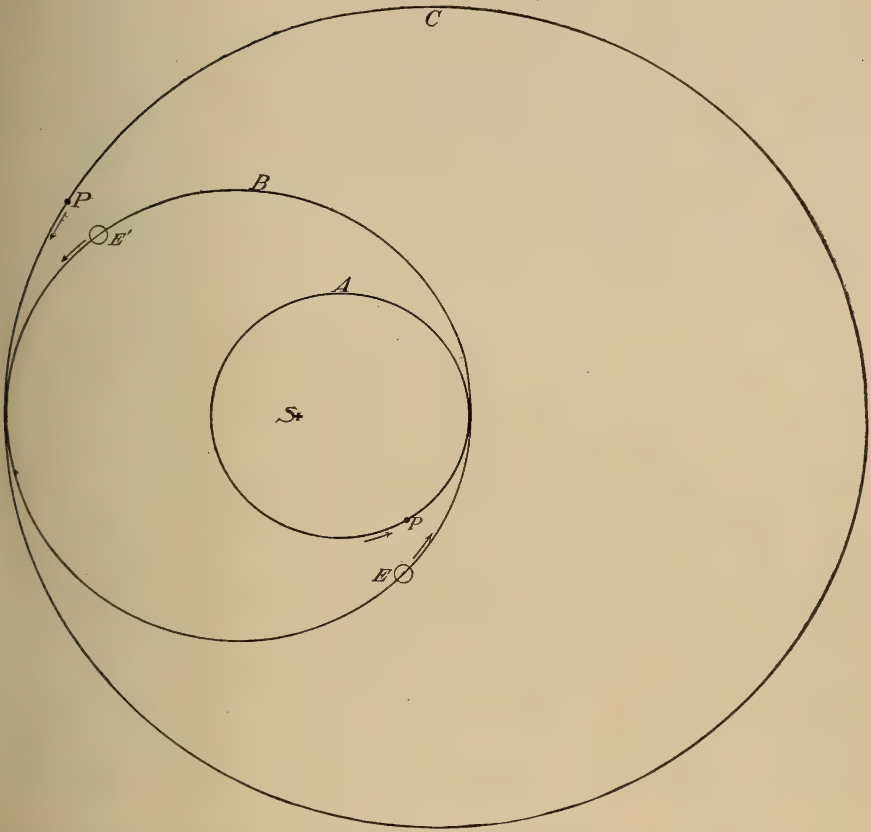

FIG. 29.—Diagram illustrating the condition under which collisions may take place in elliptical orbits of the planetary type. *S* represents the solar mass at the center of the system, *E* the planetary nucleus, *B* its orbit, *p* a planetesimal in the orbit *A*, smaller than *B*, and *P* a planetesimal in the orbit *C*, larger than *B*. The case has been so chosen as to represent at once the smallest and the largest orbits of typical eccentricity that can come into contact with the orbit of the planetary nucleus. The minimum extreme is found when the aphelion point of the small ellipse *A* coincides with the perihelion point of the orbit of the planetary nucleus *B*. In no other position can the orbit *A* touch the orbit *B*. The maximum extreme is found where the aphelion point of *B* coincides with the perihelion point of *C*. In no other position can these orbits touch. Between these limiting phases, represented by the orbits *A* and *C*, there are an indefinite number of possible planetesimal orbits that might cut the orbit *B*, but in all cases, except where the orbits were like *B*, conjunction could arise only when *a more or less* aphelion portion of an inner orbit touched or crossed a more or less perihelion portion of *B*. If the orbits were equal, the velocities at the crossings would be equal and the rotating effects would be *nil*, or neutralized, and if they were nearly equal, the difference would be slight, so that the effective cases are those of the extreme classes represented. Further explanation is given in the text.

29), can only come into contact with a planetary nucleus, *E*, in the orbit *B*, at the point where it is farthest from the sun, or its aphelion point. So likewise a planetesimal, *P*, in the large orbit, *C*, can only come into contact with the planetary nucleus, *E*, at the point where the planetesimal comes nearest to the sun, its perihelion. In the first case the planetary nucleus is at its perihelion; in the second, at its aphelion. These are chosen as limiting cases; between them there are innumerable possible intermediate ones. The two selected are the most effective in their results because the differences in the velocities are greatest, and hence they may be regarded as embracing the whole and as representative.

Now the vital point lies in the fact that, *at the point of collision*, the body in the *smaller* orbit is moving *slower* than the one in the larger orbit, though *on the average* it moves the faster. For example, the planetesimal, *P*, at the points where alone it may come into contact with the nucleus, *E*, is moving slower than *E*. If collision takes place at all, *E* must overtake *P*. This may be demonstrated by the principles of celestial mechanics,[1] but it may also be readily seen by inspection, for at the point of contact *E* has a velocity sufficient to carry it farther away from the sun through the larger orbit *B*, while the body in the orbit *A*, from deficiency of velocity, falls back towards the sun. At the points where the planetesimal, *P*, in the large orbit, can alone come into collision with the nucleus, *E*, the case is reversed, and the planetesimal, *P*, has the greater velocity, and must overtake *E*, if there is any collision at all.

The varying effects of the impacts on the rotation.—If the body in the outer orbit were always to strike the outside of the body in the inner orbit, as in the ideal cases illustrated, the impact would contribute to forward rotation; but the orbits may cross one another, and the body in the inner orbit may have passed the crossing before it is overtaken by the body in the outer orbit, and so the inertia of the overtaken body may be felt on the *outer* side of the nucleus and tend to produce retrograde rotation. It is, therefore, necessary to take account of two opposite classes of effects, and to estimate the residual influence of all probable collisions. It will be seen at once that this residual influence must be far less in magnitude than the sum of the force of all impacts, for the opposing classes neutralize one another, and hence the resulting rotation is likely to be relatively low, though the total force of impact be great. It is further evident that the result might have varied considerably in the different planets, and this is in concordance with the varying rotations actually presented by the several planets.

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[1] An elegant method of determining the velocity of a body at any point in its elliptical orbit is given on p. 139 of Moulton's Celestial Mechanics.

It is still further obvious, on inspection, that the greatest differences of velocity, and hence the greatest rotatory effects, must occur in the extreme or limiting cases of collision that occur at the perihelion and aphelion points of the nucleus' orbit; for, where the orbits have more nearly the same dimensions and the crossings are at points intermediate between these extremes, the differences of velocity are less and the rotatory effects less, whatever their phases.

The average or residual effects of collisions in the limiting cases may be gathered from the case represented at the left in Fig. 30, in which planetesimals in small orbits are *overtaken* by the nucleus near its perihelion point, and from the case at the right in which the planetesimals in the large orbit *overtake* the nucleus near its aphelion point. By inspecting the figure, it will be seen that the areas which represent the possibilities of overtake favorable to forward rotation exceed those favorable to backward rotation. This holds true on the assumption of an equable distribution of planetesimals, which may fairly be assumed as the average fact, but not necessarily as always the fact; and hence the conclusion is not rigorous, and a backward rotation is not impossible. From the nature of the case, a varying rotation for the several planets is more probable than a nearly uniform one.

It is also obvious that the impacts on the right and left sides of a growing nucleus, as well as those on the outer and inner sides, might be unequal, and hence *obliquity* of axis of rotation of varying kinds and degrees might arise. As the solar system presents these variations, the method of accretion here postulated seems to lend itself happily to the requirements of the case.

The order in which the contingencies of collision come into play—There is a supplementary factor arising from the order in which the contingency of collision arises. If a planetesimal is subject to two equal contingencies of collision with the planetary nucleus, of opposite effect, it is obvious that the one which it first encounters has a better chance of realization than the other; for if the first is realized, the second loses its chance. Now by reference to Fig. 31 it will be seen

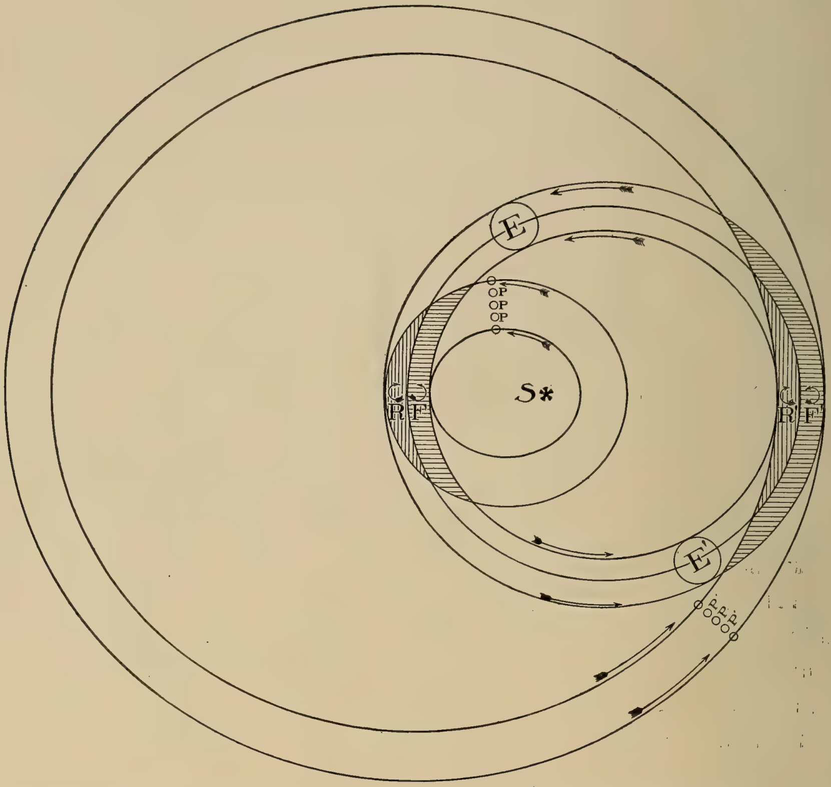

Fig. 30.—A diagram intended to illustrate the proportion of normal cases of collision that will tend to give *forward* rotation as against *retrograde* rotation, a uniform distribution of planetesimals being assumed. To avoid unnecessary complication, a belt of planetesimals in the minimum normal orbits that permit collision, and another belt of those in the maximum normal orbits that permit collision, each having the breadth of the planetary nucleus, are chosen, as these are the cases of greatest differential velocities, and hence the most effective in producing rotation. The intermediate cases are not only less effective because of less differential velocity, but because the collisions of the two classes are more nearly equal in number and more nearly neutralize one another. In inspecting, let it be noted that the nucleus, *E*, at the left, is moving faster than the planetesimals in the area of possible collision, and hence that the planetesimals which it overtakes on its inner side tend to cause forward rotation, while those which it overtakes on its outer side tend to produce retrograde rotation. The collisions in the larger area, *F*, favoring forward rotation, are much more numerous than those in the small area, *R*, favoring retrograde rotation. At the right, the planetesimals are moving faster than the nucleus *E′*, and those that overtake it on the outside in the area *F′* tend to forward rotation, while those that overtake it on the inner side in the area *R′* tend to retrograde rotation. In both cases, forward rotation is favored. If belts between these limiting belts be drawn, the difference between the two classes of areas will be less, but of the same phases.

that, in the shifting of the inner orbits, it will be possible for the planetesimals to collide with the inner side of a nucleus earlier than with the outer side, and hence forward rotation is favored. So also, by an examination of the orbits of the outer planetesimals, a similar fact

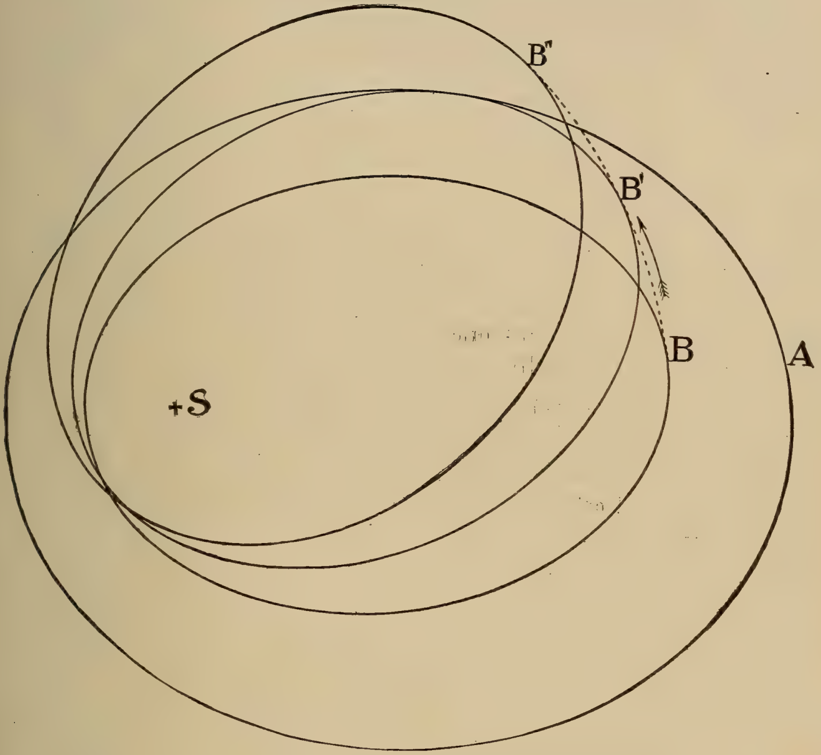

Fig. 31.—Diagram showing that in the shifting of orbits, the first contingencies of collision favor forward rotation. *B* represents a smaller elliptical orbit within a larger one, *A*. If *B* be shifted progressively in the direction *B'*, *B''*, it will first come into possible collisional relations with *A* on its inner side, and at this point a body in the orbit *A* is moving faster than a body in the orbit *B*, as shown by the large orbit the former describes, and, the collision being on the inner side, forward rotation is favored.

is made obvious. Thus the *order* in which the possibilities of collision are brought into effect favors direct rotation.

The collecting zones.—From the previous discussion it will be seen that a planetary nucleus gathers planetesimals that have orbits both smaller and larger than itself, and hence in effect it sweeps a space both outside and inside its own zone. The breadth of this space is dependent on the eccentricity of its own orbit, and on the eccentricities of the orbits of the planetesimals it gathers in on either hand.

Competitive nuclei and selective dominance.—It is obvious that there may have been two or more nuclei originally within the same zone. If one of these was notably smaller than the other, it might be picked up by the latter, the same as if it were a planetesimal. Two of equal size might perhaps unite, though this would not necessarily take place. Two nuclei in nearly the same zone must feed upon the same belt of planetesimals, and must mutually interfere with one another's growth. If there were little difference in their masses at the outset, that one which was best spaced out from the nuclei in neighboring zones would be likely to become dominant by superior growth, for it would have a better feeding-ground, so to speak. Even a nucleus that was smaller at the outset, if well separated from large competitors, might become the dominant one by a better growth.

If there were originally many nuclei of minor mass, and if these were much scattered, especially if the planes of their orbits were diverse, the dominance of any one might be avoided, and a scanty growth of all result, as in the case of the asteroids.

The shifting of orbits.—It seems to be a sure inference that, in the process of growth, the nucleus must have *worked towards the center of the zone* from which it gathered, as a consequence of the superior feeding on the richer side. For example, if more planetesimals were picked up on orbits smaller than its own, its orbit must have grown smaller as a mechanical result of the accretion, for a new orbit, arising from the union of two bodies, is intermediate between the two previous orbits, and hence smaller than the larger one. If more planetesimals were picked up on the outer side, the orbit of the nucleus must have grown larger. The nucleus, therefore, must have worked toward the center of the richer feeding-ground, or in average cases of equable original distribution, toward the ground not preyed upon by other nuclei.

The spacing-out of the planets.—The foregoing processes tended toward a selection of nuclei for dominance, and to an automatic spacing-out of the successful nuclei. This process, if our hypothesis be true, should find verification in the actual distribution of the planets, and be an explanation of it. This distribution should correspond to the eccentricities of the nuclei, modified by the proportions of planetesimals of larger and smaller orbits gathered in by them. Assuming these to have been somewhat equable, the planetary distribution should be roughly proportional to the eccentricities of the nuclear orbits. As a basis for inspection, let it be supposed that the collecting zone of each planet reaches half-way to its neighbor on either hand; and let the eccentricity of the orbit of each nucleus be such that the nucleus itself shall sweep its whole collecting zone, which is more than the case absolutely requires. The following are the eccentricities so derived, compared with present eccentricities:

	Assigned Eccentricity.	Present Eccentricity.
Nucleus of Mercury	.25 ±	.2
Venus	.21	.006
Earth	.20	.017
Mars	.28	.093
Asteroids (mean)	.33	.38 } and less; mean about .15
Jupiter	.336	.048
Saturn	.366	.056
Uranus	.37	.046
Neptune	.38 ±	.009

There being no known planet outside of Neptune, the method can only be applied to it by an arbitrary assumption regarding its outside collecting area. It may be reasonably assumed that the nucleus of Neptune represented the head of the protuberance, so to speak, and that its accretion was essentially all on the inner side, which would draw its orbit inward, according to the principle above stated. This may account for its anomalous spacing out. There being no known planet inside Mercury, the eccentricity assigned it is also in a measure arbitrary.

With these qualifications, it will be seen that the assigned eccentricities are quite harmonious, and on the whole they indicate a progressively greater original eccentricity from within outward. By comparison with the existing eccentricities, it will be seen that the assigned original ones are much the more consistent. The reason for this, under our hypothesis, is close at hand. According to the principle of evolution from eccentricity toward circularity, stated above, the greater the accretion, the greater the progress toward circularity. This is qualified somewhat by the perturbations which the planets create in one another's orbits, and by the special conditions of aggregation, but remains essentially true. For the large planets that have dominated their collecting zones and presumably swept them thoroughly, the reductions of eccentricity are subequal. For the very small bodies that presumably grew but little, *the eccentricities remain large,* for the greater part. For example, the eccentricity of Mercury, the smallest of the planets, remains more than twice that of any other planet. Mars, the next smallest in size, comes next in eccentricity among the planets, while the asteroids, that probably grew but little, have high eccentricities as a rule. Their orbits have doubtless been not a little disturbed by the great influence of their powerful neighbor Jupiter, and a rigorous application of so general a law as the one under consideration cannot be made to the details of their orbits; but the tenor of the facts is very suggestive. The highest eccentricity, .38, is as high as the highest eccentricity assigned to the original nuclei of the planets. Of the 70 asteroids whose diameters are fairly well known, the half that are larger, and presumably have grown most, have orbits less eccentric by 13.7 per cent. than the half that are smaller, and presumably have grown less. Of the orbital elements of 278 asteroids examined, the half having the lowest inclination to the common plane of the system, and so best situated for accretion, have eccentricities 21.9 per cent. less than those of greater inclination. The orbits of Neptune and Venus are exceptionally circular, the former perhaps on account of its outermost position and mode of accretion, as previously suggested, the latter for reasons not obvious. Rigorously consistent results cannot be expected from such antecedents as are postulated in a case of this kind. The degree of consistency noted is perhaps to be regarded as much more remarkable than the departures from it. If this view of the spacing out of the planets be entertained, a rational law may be substituted for the purely numerical formulation, known as Bode's law, viz., that *the spacing has been derived from a fairly consistent variation in the primitive eccentricities of the planetesimals and nuclei of the parent nebula, in which the outer were symmetrically greater than the inner.*

SUMMARY.

The planetesimal hypothesis thus assumes that the solar system was derived from a nebula of the most common type, the spiral, and that the matter of this parent nebula was in a finely divided solid or liquid state before aggregation, in harmony with the continuous spectra of spiral nebulæ. It regards the knots of the nebula as the nuclei of the future planets, and the nebulous haze as matter to be added to these nuclei to form the planets. It assumes that both the knots and the particles of the nebulous haze moved about the central mass in elliptical orbits of considerable, but not excessive, eccentricity. It postulates a simple mode of origin of the nebula connected with the not improbable event of a close approach of the ancestral sun to another large body, but the main hypothesis is not dependent on this postulate.

It assigns the gathering-in of the planetesimals to the crossing of the elliptical orbits in the course of their inevitable shiftings. Out of this process and its antecedents, it develops consistent views of the requisite distribution of mass and momentum, of the spacing out of the planets, of their directions of rotation, of their variations of mass, of their varying densities, and of other peculiarities.

It deduces a relatively slow growth of the earth, with a rising internal temperature developed in the central parts and creeping outward. With such a mode of growth, the stages of the earth's early history necessarily depart widely from those postulated by the Laplacian and the meteoritic hypotheses. These stages now claim our attention.

CHAPTER II.

THE HYPOTHETICAL STAGES LEADING UP TO THE KNOWN ERAS.

The hypotheses of the earth's genesis having now been sketched, the several stages of evolution that led up to the beginning of the legible record of Archean times claim attention. These stages are as yet hypothetical, and the views presented are to be entertained with appropriate reserve. The study of these stages is none the less imperative, for during them the broader phases of the earth's dynamics were brought into action, the essential features of its configuration were determined, and even the salient lines of its relief were marked out; and these have been perpetuated, in their grander features, to the present time. Since these dominant characters were the outgrowth of the preceding history, they are to be interpreted according as (1) the forming earth is thought to have followed the gaseo-molten path, with cooling as its great event, or (2) to have grown up by accessions, with increasing heat and gravity as its leading features. No other than these two lines of development seems to require serious consideration at present, for, however the genetic process started, it probably glided into the one or the other of these alternative phases before the era was reached which gave to the earth its final form. It remains, therefore, to outline in succession (I) the stages of early evolution under the gaseo-molten hypothesis, as commonly held heretofore; (II) a modification of these stages designed to escape difficulties raised by recent investigations, and (III) the stages under the accretionary hypothesis.

I. STAGES UNDER THE COMMON FORM OF THE GASEO-MOLTEN (LAPLACIAN) HYPOTHESIS.

The hypothetical stages arising from the Laplacian view have nowhere been stated more definitely and succinctly than by Professor Dana,[1] and his synopsis is here introduced as a typical statement of the general conceptions that have been entertained by the majority of geologists during the past century.

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[1] Manual of Geology, 4th edition, pp. 440, 441.

"I. The *Astral* æon, as it has been called, or that of the fluid globe having a heavy vaporous envelope, containing the future water of the globe or its dissociated elements, and other heavy vapors or gases.

II. The *Azoic* æon. Without life.

1. The *Lithic Era:* commencing with the earth a solid globe, or at least solid at the surface; the temperature at the beginning above 2500° F.; the atmosphere still containing all the water of the globe (amounting to 200 atmospheres, according to Mallet, 1880), all the carbonic acid now in limestone and that corresponding to the carbon now in carbonaceous substances and organic substances (probably 50 atmospheres), all the oxygen since shut up in the rocks by oxidation, as well as that of the atmosphere and of organic tissues. The time when lateral pressure for crustal disturbance and orographic work was begun; when 'statical metamorphism,' or that dependent on heat of a statical source,—the earth's mass and the vapors about it,—began.
2. The *Oceanic Era:* commencing with the waters condensed into an ocean over the earth, or in an oceanic depression, with finally some emerging lands,—the temperature perhaps about 500° F., if the atmospheric pressure was still 50 atmospheres. The first of tides and the beginning of the retardation of the earth's rotation. Oceanic waves and currents and embryo rivers begin work about the emerged and emerging lands; the large excess of carbonic acid and oxygen in the air and water a source of rock-destruction; before the close of the era, the formation of limestones and iron-carbonate by chemical methods, removing carbonic acid from the air and so commencing its purification; the accumulation of sediments without immediate crystallization or metamorphism, and thereby the beginning of the earth's *supercrust.*

III. The *Archæozoic* æon. Life in its lowest forms in existence.

1. *The Era of the First Plants:* Algæ, and later of aquatic Fungi (Bacteria), commencing with the mean temperature of the ocean at possibly 150° F., since plants *now* live in waters up to and even above 180° F. Limestones formed from vegetable secretions, and silica deposits from silica secretions; iron carbonate, and perhaps iron oxides formed through the aid of the carbonic acid of the atmosphere and water; large sedimentary accumulations, where conditions favored, thickening the supercrust.
2. *The Era of the First Animal Life:* mean temperature at the beginning probably about 115° F., and at the end 90° F., or lower; limestones and silica deposits formed from animal secretions; deposits of iron-carbonate and iron-oxides continued; large sedimentary accumulations."

DIFFICULTIES ENCOUNTERED BY THE GASEO-MOLTEN HYPOTHESIS.

Quite apart from the question of its general truthfulness, two sources of serious dissatisfaction with the preceding view of the early earth-stages have grown out of recent investigations, the one arising from failure to find any great basal formation bearing the distinctive characters of an original crust; and the other, from adverse evidence relative to the prodigious atmosphere postulated.

1. *Evidence Relative to an Original Crust.*

The theory of a molten earth carries the presumption that the liquid mass arranged itself in concentric layers according to the specific gravities of the constituents, if convection was not so vigorous as to prevent this. As the granitoids constitute the lightest class of igneous rocks, their molten magma has been, very consistently, assigned to the outer zone of the molten earth,while the magmas of the heavier neutral and basic rocks have been assigned to lower layers. This conception was long ago set forth definitely by Durocher, who postulated an outer zone of rock derived from an "acid magma", and a lower zone derived from a "basic magma."[1]

If, however, it be assumed that convection was too effective to permit such concentric arrangement of liquid layers, the conception of an intimate mixture of material must be substituted for that of differentiated layers, but the outer zone of rock must probably still have been homogeneous in the larger sense, for the conception of *permanent* areas of lighter rock in one region, and heavier rock in another, at the same time and in the same horizon, is inconsistent with the principles of hydrostatic equilibrium.

The theoretical crust a universal identifiable substratum.—In either case, a characteristic surface of lava, either sensibly homogeneous or homogeneously mixed, and in approximate hydrostatic equilibrium, should have constituted the material which solidified into the original crust. This crust should, therefore, be a universal substratum of a distinctive character and susceptible of definite identification. A specially complete state of crystallization, of the very coarse type, seems to be a necessary attribute of a rock formed from a molten globe, except at the very surface, for the process of cooling must have been very slow, and the conditions for the growth of the crystals most propitious. The primitive formation should hence be of the most massive and declared holocrystalline type. Its distinctive character could scarcely be disguised beyond recognition by any probable katamorphism at a later date.

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[1] A clear statement of this logical view is given in Haughton's Manual of Geology, p. 3, to which is added a translation of Durocher's notable essay on comparative petrology, in which the doctrine is elaborated.

The limitations of pyroclastic concealment of the crust.—No very large amount of scoriaceous and fragmental material can be assumed to have been heaped upon the original crust consistently with the hypothesis *in the form above stated;* for the assumption that the primitive atmosphere contained all the future water of the hydrosphere leaves no appreciable explosive agency in the molten globe to produce such material. The atmospheric and hydrospheric constituents, by the terms of the hypothesis, had either never condensed, or had been thoroughly boiled out of the white-hot mass. This is not an undue forcing of the mere phrasing of the hypothesis, for not a few familiar doctrines and working conceptions have been built upon the assumed exclusion of the hydrospheric and atmospheric constituents from the primitive rocks. The permanent concealment of the original crust under pyroclastic material cannot, therefore, consistently be assumed without modifying the hypothesis, for many thousand feet have been eroded from the surface of the oldest known areas.

The adverse bearing of recent discoveries.—Until recently, the great granitoid areas of the Archean series were thought to meet very fairly the theoretical requirements of the case; but it has been discovered in no less than five of the regions most critically studied, that many of these great granitoid masses are *intrusive,* and that they have been forced into rocks that were formed *on the surface* by lava outflows, volcanic fragmentation, or surface sedimentation. This significant discovery was made almost contemporaneously by geologists of Canada, the United States, Great Britain, Scandinavia, and Finland. While such an intrusive nature has not yet been proved for all the great granitoid masses of all Archean areas, the presumption now lies in that direction. The new interpretation thus reduces to an unknown, if not a vanishing quantity, the area of massive crystalline rock that can, with plausibility, be referred to the supposed original crust. But the theoretical necessity for a large area of such rocks, if the molten hypothesis in this form is to be retained, has, at the same time, grown more imperative with progressive investigation; for it is obvious that all the vast series of sediments must have been derived from the original crust and from such extrusions as have since come from beneath it, and it is becoming more and more evident that the original source of the main portion of this material was the present land area and its immediate borders. There is now no satisfactory evidence of any *general* reversal of continental and oceanic areas, as was once rather freely postulated. Abysmal deposits do not appear in the continental series, if one or two equivocal cases be set aside; and if abysmal areas have not been added to the continents, continental areas cannot have been sunk to abysmal depths, without destroying the critical relations of the sea to the land which seem to have been constantly maintained. There is now, therefore, little or no plausible ground for supposing that large abysmal portions of the crust were thrust up into high land and supported there till great sedimentary series were derived from them, and then withdrawn to abysmal depths again. This argument should not be pushed so far as to shut out mutual encroachments and recessions of *shallow* sea on land—which have been numerous—nor minor changes in the relations of the deep basins and the continental platforms; but it is probably quite safe to conclude that the sediments now buried beneath the sea, and not reckoned in the known series, are greater in amount than any sediments that may have been derived from portions of the primitive land areas now buried beneath the sea; in other words, it is probably quite safe to assume that at least as much derivative material as is now represented by the known sediments, has come from the present land areas. There should, therefore, be large areas of the original crust now occupying the surface, and still other areas lying beneath the sedimentary series in such a way as to be accessible incidentally here and there. If the trend of further investigation shall follow the present tendency, and exclude the accessible rocks of the Archean areas from the original crust, the molten theory, in its original form, will have lost its observational support.

2. *Atmospheric Difficulties.*

The second point of growing dissatisfaction is a corollary of the preceding one, for both spring from the assumption that the atmospheric and hydrospheric gases were excluded from the molten globe. It is on this ground that the primitive atmosphere is held to have been vast, hot, and heavy, and to have contained all the water of the globe, all the carbonic acid now in limestone, and that corresponding to the carbon now in carbonaceous deposits and in organic substances, all the oxygen since shut up in the rocks by oxidation, as well as that of the atmosphere and of organic tissues (p. 83). The assumption back of this seems to be that heat always promotes gaseous expulsion, and if so, the separation of the gases from the extremely hot molten rock should certainly have become most complete in the white-hot primitive globe. Under this view, absorption, rather than expulsion, should have been the rule in all later and colder states. This fundamental conception has been widely entertained, and has found familiar expression in certain volcanic hypotheses, in the supposed absorption of a former atmosphere and hydrosphere of the moon into that body, and in well-known prophecies of a similar doom for the envelopes of the earth.

The adverse evidence of early life.—The more the physiological functions and adaptations of the early life are compared with those of modern life, the more nearly identical they appear to be, and the more scant has become the basis for postulating profoundly different atmospheric and thermal conditions in early times. This observation is not confined to the discovery of air-breathing animals far back in geologic history, when a prohibitive excess of carbon dioxide should, theoretically, have still remained in the air, but relates as well to various adaptations found in nearly all forms of life, plants not less than animals. For example, the xerophytic organs of some plants that lived in the later half of the Paleozoic era are perhaps as irreconcilable with a vast hot vaporous atmosphere, overcharged with carbon dioxide and water-vapor, as is the presence of the flying insects with their extremely active organizations.

Incongruities on the physical side.—An atmosphere so heavily surcharged with carbon dioxide and water-vapor must have been rich in heat-absorbing power, and should have given a very warm, equable climate to the earth, as has been rightly assumed. Warm equable climates did indeed prevail in a *portion* of the earlier history of the earth, as also in the later; but the investigations of the past two decades in India, Australia, and South Africa have forced the recognition of extensive glaciation *on the very border of the tropics*, at a period as early as the closing Paleozoic. Evidences of glaciation in northwestern Europe, and also in China in about 30° N. Lat., at or near the base of the Cambrian, has recently been presented. Less striking, but perhaps not less significant, is the occurrence in the early Paleozoic, of extensive salt and gypsum beds in rather high latitudes. These deposits seem to imply severe and protracted aridity, and such aridity, especially where north of the 30° belt, is not readily reconcilable with an enormous equalizing atmospheric envelope.

There seem, therefore, to have been, in Paleozoic times, much the same alternations of very uniform with very diversified climates that marked the Mesozoic and Cenozoic eras; in other words, the alternations of climate seem to have been of much the same order throughout the known eras. The hypothesis of an enormous original atmosphere suffering gradual depletion finds, therefore, but scant and uncertain support in a critical study of either the biological or the physical history of the earth.

II. A MODIFICATION OF THE PRECEDING VIEW.

Can the gaseo-molten hypothesis be modified to meet these difficulties? The especially troublesome phases of the hypothesis arise from the assumption that the atmospheric and hydrospheric gases were kept out or forced out of the hot molten globe, and so constituted a vast atmospheric envelope. If amendment be possible, it must apparently consist in assuming that lavas, *however hot,* may hold large quantities of gaseous constituents which may be discharged later. Existing lavas bring to the surface great volumes of absorbed gases. They are disposed to discharge these, however, for the greater part, under usual surface conditions; but the limits of this disposition are not yet well understood; indeed, the whole subject of the absorption and retention of gases in molten rock is imperfectly mastered. It is not inconsistent, however, with present knowledge to suppose that a molten globe of rock, arising from vaporized rock-substance, might retain large quantities of the atmospheric gases so long as it remained in the liquid state, and part with them only when it solidified. It is admissible to go even further, and assume that much of the atmospheric material might remain occluded in the solid rock after congelation, since igneous rocks now contain notable quantities of gas. By making these assumptions, it may be held that during the molten state the gases were not fully separated from the molten mass, but that the gases in the molten globe and those in the atmosphere above took on a state of equilibrium relative to one another, the special terms of which are as yet unknown, but which were of such an order that a large part of the future atmosphere and hydrosphere was retained within the body of the earth. When, later, the external atmosphere was consumed by reaction on the surface rocks, the previous equilibrium was destroyed, and any residue of liquid material, charged under the previous condition, would, when freed from confinement, discharge an additional part of its gases. That portion of the mass which solidified under the earlier conditions of equilibrium may also be supposed to have retained much gaseous material, which was freed later under suitable conditions. Under this conception, the primitive atmosphere was much less extensive than that postulated by the standard form of the hypothesis, and much more gaseous material was held in reserve in the earth-body to actuate future vulcanism and to feed the atmosphere and hydrosphere.

With this basis, the modified view supposes that the formation of the crust was followed by a period of exceptional volcanic activity, and that this volcanic stage was so prolonged and so effective that the primitive crust was deeply buried under volcanic extrusions, and has since been rarely, if at all, exposed, and that the sedimentary series was derived chiefly from the volcanic series. Some of the extruded material is supposed to have constituted lava-flows and some of it massive embossments, while much of it consisted of the fragmental products of the explosive gases. As the series was built up, it became subject to intrusions forming dikes, sills, and batholiths. When the surface temperature had fallen below the boiling-point of water, aqueous action gave rise to sedimentary deposits which mingled, as minor elements, with the dominant volcanic constituents.

These features fit fairly well the characteristics of the earliest known rocks, as now interpreted. If this supplemental volcanic action be made extensive enough, the difficulty arising from the apparent absence of the rocks of a primitive crust is avoided.

The hypothesis thus modified is not altogether successful in meeting the atmospheric difficulties mentioned above (p. 86), for the primitive atmosphere, supplemented by the accessions of this great volcanic period, should have given a vast gaseous envelope, and hence a history not altogether unlike that of the preceding view, though less excessive in its terms.

The modified hypothesis furnishes a better ground than the older view for elucidating the volcanic activity of later periods, and for supplying the loss of the atmosphere due to chemical combination with the surface rocks; but it is not clear that it is adequate. The modification is offered as a possible emendation of the more common phase of the gaseo-molten hypothesis touching two radical points where the latter seems to fail to meet the requirements of advancing knowledge.

Stages under the Modified Hypothesis.

The stages of evolution under this view may be summarized as follows:

I. **The astral eon.**—The separation of the material of the earth from the parent nebula and its aggregation into a rotating gaseous spheroid.

II. **The molten eon.**—The condensation of the rock matter of the gaseous spheroid into a molten spheroid which was surrounded by a hot vaporous atmosphere; but the molten spheroid nevertheless retained, occluded within itself, some large part of the water of the present hydrosphere, as well as much of the carbon dioxide represented by the present carbonates and carbonaceous deposits.

III. **The lithic eon.**—The solidification of the molten spheroid, beginning most probably at the center, on account of pressure, and possibly continuing thence to the surface, but perhaps beginning also at the surface, at a later stage, and solidifying downwards, the two solidifying portions at length meeting, or partially meeting, giving rise to essential solidity of the whole. In this respect, the theory may be accommodated to the various phases of opinion on this subject. The first mode of solidification is not altogether favorable to the modified hypothesis, for the solidification rising from below might not improbably force out the larger portion of the absorbed gases while the surface was yet liquid The view that the surface crusted over while yet there was at least a deep molten layer below, best fits the general conception, and is the main basis for the following postulate.

IV. **The primitive volcanic eon.**—Prodigious volcanic action, closely following the solidification of the crust, during which the forcing out of lavas from below by the progressive crystallization of the remaining magma, or by plutonic stresses, was the leading event, the result being great beds of lava and tuffs on the surface, and later great intrusions of other lavas into and through these. The surface flows were formed largely of the more fluent lavas, and hence were generally of the basic or neutral class, and the pyroclastics were predominantly of the same type, while the intrusions were more largely, though not wholly, of the stiff acidic type. Later, under metamorphic action, the basic lavas became schists in part, and the acidic gneisses, neither class, however, excluding the other. Contemporaneously with this volcanic action, but quite subordinate to it, atmospheric and hydrospheric action is postulated, resulting in sedimentary deposits interlaid with the volcanic, but in greatly inferior quantity. The presence of life is implied by carbonaceous elements in the sedimentaries. This period corresponds to the Archeozoic eon, as limited by those geologists who separate the Archeozoic from the Proterozoic (Algonkian) system.

V. **The sedimentary eon.**—The remaining time, reaching to the present, is characterized by the dominance of atmospheric and hydrospheric action over volcanic, and is recorded by the ordinary clastics, sandstones, mudstones, etc., derived from well-decomposed rocks, and by limestone. It begins with the Proterozoic sedimentaries and extends to the present time, embracing the Paleozoic, Mesozoic, and Cenozoic systems.

Under this scheme, the accessible record is made to begin with some stage of the volcanic eon, but probably not the earliest.

III. STAGES OF GROWTH UNDER THE ACCRETION (PLANETESIMAL) HYPOTHESIS.

It is theoretically possible that the earth may have grown up by accessions in ways other than those sketched under the planetesimal hypothesis, as set forth in this work, and so it is necessary to recognize that accretionary evolution is not necessarily identical with planetesimal evolution, but the latter is taken as a type form and furnishes the basis for the following sketch of evolutionary stages.

I. THE NUCLEAR STAGE.

Under the planetesimal hypothesis, the earth is supposed to have started as a nebular knot, acting as a nucleus, and to have grown gradually to its present mass by accessions. It does not seem to be important, geologically, to consider the special state of the nebular nucleus if it be granted, for the reasons previously assigned (p. 62), that it constituted only a small fraction of the grown planet. If its mass were quite small, there is reason to assume that it was composed of material of high molecular weight, since light molecules would probably escape by virtue of their high velocities, except as they were coherent with, or occluded in, heavier material. The nucleus is supposed to have been originally an assemblage of planetesimals grouped together by their mutual gravity, and to have passed gradually into a solid nucleus in connection with the capture of outside planetesimals. As the planetesimals were solid aggregates in the main, and only partially elastic, their collisions mutually destroyed their orbital motions in a certain proportion of cases, and led to their collection at the center. In other cases the orbital motions were increased, but any planetesimals which were thus temporarily driven away were subject to subsequent capture.

II. A POSSIBLE ATMOSPHERELESS STAGE.

As the solid nucleus thus formed may not have been massive enough to control a gaseous envelope in its earlier stages, a possible atmosphereless stage is to be recognized. Just how massive a planetary body must be to hold permanently an appreciable atmosphere is not accurately computable at present, because of the uncertain value of some of the factors involved.[1] A fairly safe conclusion may perhaps be drawn from known celestial bodies. The moon (1/81 of earth's mass) has no detectable atmosphere, nor has any smaller body, whether satellite or asteroid, so far as known. Mars (1/9.34 of earth's mass) has an appreciable but apparently quite limited atmosphere. The limit between atmosphereless and atmosphere-bearing bodies probably lies between the two, i.e., roundly, between 1/80 and 1/10 of the earth's mass.

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[1] The following papers bear upon this subject: G. Johnstone Stoney, On the Cause of the Absence of Hydrogen from the Earth's Atmosphere, and of Air and Water from the Moon, Roy. Dublin Soc., 1892. G. Johnstone Stoney, On Atmospheres upon Plants and Satellites, Trans. Roy. Dublin Soc., 2 series, 6, 1897; *Ibid.*, 1898, p. 305. T. C. Chamberlin, A Group of Hypotheses bearing on Climatic Changes, Jour. of Geol., Vol. V, 1897, p. 653. G. Johnstone Stoney, On the Presence of Helium in the Earth's Atmosphere, and its Relation to the Kinetic Theory of Gas, Astrophys. Jour., Vol. VIII, Dec. 1898, p. 316. S. R. Cook, On the Escape of Gases from Planetary Atmospheres according to the Kinetic Theory, Astrophys. Jour., Vol. XI, Jan. 1900, p. 36. G. Johnstone Stoney, On the Escape of Gases from Planetary Atmospheres According to the Kinetic Theory, No. I, Astrophys. Jour., Vol. XI, May 1900, p.

The mass of Mercury, unfortunately, is not known with satisfactory accuracy, because it has no satellite and offers no other ready means of determination. Values all the way from 1/26 to 1/9 of the earth's mass have been assigned. Mercury gives no distinct signs of atmospheric refraction, and its reflection of light (albedo) is very low, even lower than that of the moon, and, like that of the moon, is relatively much stronger for surfaces normal to the line of incidence and of vision than for those oblique to it, which is characteristic of a rough surface. All this implies the absence of an atmosphere and hydrosphere of sufficient value to give effective reflection of themselves, or to develop a good reflecting body by smoothing down the surface and filling up the pores. On the other hand, certain lines of the planet's spectrum have been thought to imply the presence of water-vapor, but this is not conclusive. The probabilities seem to be that Mercury has no atmosphere that is effective as a weathering or degradational agent, which is the point of geologic interest. This brings the limit of appreciable atmosphere much nearer Mars than the moon, and justifies the provisional conclusion that if the young earth had no more than 1/20 of its present mass it probably possessed no atmosphere of appreciable geological efficiency, but that, when it had gained 1/10 of its present mass (radius probably about 2100 miles) an appreciable though relatively slight atmosphere surrounded it.

III. THE INITIAL ATMOSPHERIC STAGE.

The origin of the atmosphere.—The origin of the atmosphere under the gaseo-molten line of evolution has become familiar. Its origin under the accretion hypothesis is so different as to present more points of contrast than of similarity. When the growing earth reached a

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251; No. II, *Ibid.*, June 1900, p. 325. G. Johnstone Stoney, Note on Inquiries as to the Escape of Gases from Atmospheres, *Ibid.*, Vol. XII, October 1900, p. 201.

mass sufficient to control the flying molecules of atmospheric material, there were two sources from which these could be supplied for the accumulation of an atmosphere, an external and an internal one.

1. **External source of supply.**—By hypothesis, all the atmospheric and hydrospheric material of the parent nebula which was not gathered into the aggregated planetesimals remained as free-molecular planetesimals. While the planetary nucleus was small, it could not gather and hold the lighter molecules, even when they collided with it, except as this was done by occlusion or surface tension, in which case they did not form an atmosphere. But when the growing earth reached the requisite mass, these free atmospheric molecules were gathered about it and retained as an atmospheric envelope. This would be a more abundant source of supply during the nebular stages than afterwards, but, by hypothesis, it continues to be a source of some supply even to the present time, for the very doctrine that postulates the loss of such high-speed molecules implies their presence in space subject to capture by bodies capable of capturing them.

The planetesimals originated, by hypothesis, from gaseous matter shot forth from the ancestral sun. Those portions which condensed into aggregated planetesimals probably occluded within themselves some atmospheric material, much as meteorites and crystalline rocks of the earth do. These planetesimals were doubtless highly heated on striking the earth's surface, or on entering its atmosphere after it began to gather one, and were thus probably forced by the acquired heat to give up a part of their gases, as meteorites and rocks do when heated. These expelled gases would be an additional source of supply; but the planetesimal material on cooling might be disposed to re-absorb gases, and the final result might be little or no gain; at least this seems an uncertain source of supply.

2. **Internal source of supply.**—As the planetesimals were gathered into the growing earth-nucleus, they carried their occluded gases in with them, except as the superficial portion might be set free by the heat of impact. There were thus built into the growing earth atmospheric materials. So also, while the nucleus was growing, it was subjected to the bombardment of free molecular planetesimals of the atmospheric substances. In its early stages it might not be able to hold these as a free gaseous envelope, but to a certain extent, it could hold, by virtue of capillary and subcapillary attraction, such mole-

cules as were driven into the pores and other interstices of the fragmental surface arising from the infall of the planetesimals.

The extent to which gases may be held condensed in small solid bodies is shown by meteorites and igneous rocks to be large. Meteorites carry, on the average, several times their volumes of condensed gas; so do many, probably most, igneous rocks of the earth (Vol. I, pp. 619–620).[1] The testimony of the meteorites is peculiarly significant here, for they have traversed unknown depths of space in a practical vacuum, in addition to the vicissitudes of their origin and the heating of their fall. Atmospheric material is carried into the earth's body by them to-day in quantities that are large, relative to their masses. Their testimony becomes the more significant if we accept that view of their origin which makes them but the fragments of small atmosphereless bodies, built up precisely as the early earth was under this hypothesis. This view makes them specific samples of the products of the assigned process.

The atmospheric material thus condensed within the growing earth could become a part of the atmospheric envelope only by extrusion. The assigned modes of extrusion will be considered presently; meanwhile it may be assumed that these internal gases were given forth progressively, and fed the atmosphere.

The nature of the initial atmosphere.—The contribution made by the external source of atmospheric material might include any constituent of the ancestral sun that could remain free in the nebula, and be picked up and held by the earth. Some portion of the constituents of the present atmosphere may therefore be assigned to this source. In what ratio these constituents were contributed to the nebula probably depended on their proportions in the ancestral sun, or rather their proportions in that part of the ancestral sun that was dispersed to form the parent nebula. Concerning this little can safely be said. Hydrogen is apparently very abundant in the outer part of the sun, but it is doubtful whether the earth can, even now, hold hydrogen in a free state permanently in any large amount. Of the proportions of the common atmospheric constituents in the sun, in a free state, little is known.

[1] An ampler series of analyses of gases occluded in rocks, now being made by R. T. Chamberlin, confirms previous results and seems to foreshadow the conclusion that these gases are retained with much tenacity, but are given up on the complete weathering of the minerals holding them.

The gases chiefly occluded in meteorites and in the crystalline rocks (Vol. I, pp. 619–620) are hydrogen, carbon dioxide, carbon monoxide, in leading amounts, and marsh-gas and nitrogen, in small quantities. It is assumed that the gases of the aggregated planetesimals, and hence those of the interior of the early earth, were of the same order of abundance. There is experimental ground for believing that, at the right temperatures and pressures, hydrogen would take oxygen from ferric oxide (which, from the analogy of igneous rocks and meteorites, may be presumed to have abounded in the earth-material) and therewith form water. The gases extruded from the interior should, therefore, have been largely water-vapor and the carbon oxides, with minor quantities of hydrocarbons and nitrogen. To these might be added such chlorine, sulphur, and other temporary gases as the volatile ingredients of the rock-material might contribute through volcanic action; but these chemically vigorous constituents would doubtless soon disappear by union with the rock-material. It is probable that carbon monoxide would pass into carbon dioxide, as it does not now accumulate in the atmosphere, although abundantly produced. The marsh-gas also disappears in some way.

Summary of available material.—The material of internal derivation available for the atmosphere, therefore, embraced chiefly water-vapor, carbon dioxide, and nitrogen. Oxygen is now given forth in some abundance by volcanoes, but it is not known whether it really comes from the interior, or has merely been carried down from the surface. The reduction of ferric oxide under certain conditions (the reverse of the process by which water is assumed to have been formed) might possibly give free oxygen.

The material of external derivation might probably embrace all the atmospheric constituents, but in proportions unknown.

The actual proportions of the atmospheric gases determined by the earth's gravity.—In determining the actual proportions of the constituents of the early atmosphere, the abundance of the supply was probably less decisive than the power of the earth to hold the individual gases. As the gravity gradually increased by the earth's growth from an incompetent minimum, its power to control the heaviest molecules with the lowest velocities was acquired before its ability to hold the lighter ones of higher velocities. According to the kinetic theory, molecular velocities vary inversely as the square root of the molecular weights. Assuming this to be correct, the leading constituents would be held in the following order, it being noticed that *molecules,* not atoms, must be dealt with.

Molecules.	Molecular weights (in round numbers).	Average molecular velocities at 0° C. in cm. per sec.
CO_2	44	33,259
O_2	32	39,155
N_2	28	41,735
H_2O	18	56,522
H_2	2	169,611

The commingling of the gases introduced some modifications of the limitations of retention, and these were favorable to the lighter gases, but the refinements of the case are of no moment here.

Carbon dioxide would be held some appreciable time before oxygen, and still longer before nitrogen, and all these a notable time before the vapor of water. The inference is that the initial atmosphere was very rich in carbon dioxide, for an abundant supply was correlated with a superior power of retention.

The amount of nitrogen occluded in rocks and meteorites is relatively small, and it was perhaps a small constituent of the early atmosphere. Owing to its chemical inertness, it may be supposed to have been increasing ever since, and thus to have attained its present dominance. A similar history may be assigned to the other, and even more inert, elements, argon, neon, zenon, krypton, and helium, of which the supplies seem to have always been very limited.

After the earth acquired the power of holding water-vapor, the supply being abundant, accession doubtless went on for a time as fast as the capacity to hold increased.

The amount of oxygen in the early atmosphere is more uncertain from doubt as to the sources of supply. Crystalline rocks and meteorites are not known to contain it in a *free* state. As above remarked, it occurs among volcanic gases, but it is not known that it comes from the deep interior. It is detected in the sun, and not improbably existed in the nebula, from which it might have been gathered shortly after the accretion of carbon dioxide began. The safer inference seems to be that it was not very abundant, relatively, in the very earliest atmosphere There are two ways in which it might have been effectively increased: (1) The impact of the planetesimals would be felt at their highest velocities by the molecules of the atmosphere in its outer part, where the opportunities for escape were greatest. The velocities of the planetesimals may have been several miles per second in many cases. In a certain proportion of cases, the planetesimals would strike the molecules in such a way that the rebound of the latter would combine a large proportion of the planetesimal velocity with their own previous velocity, and would therefore increase their liability to escape from the control of the young earth. Now in the impact of the molecules of watery vapor with the planetesimals, particularly when the latter had acquired a white-hot temperature, the heat was sufficient to dissociate the oxygen and hydrogen in considerable proportions, and these dissociated elements would take on the velocities appropriate to their respective weights, and would act individually until reunited. The mean velocity of hydrogen is more than four times that of oxygen, and it may be assumed that it would be at least four times as liable to escape from the control of the earth. Such excessive escape would leave a surplus of oxygen, even after the hydrogen that did not escape had reunited with oxygen, as it would in time. As the planetesimal impact was, by hypothesis, a very pronounced phenomenon during the growing stages of the earth, it is assumed that a notable amount of free oxygen might be accumulated by this dissociative and selective process, and that this, with that from other sources, would suffice for the support of the earliest plant life, which, though feeding chiefly on carbon dioxide, required oxygen.

(2) As soon as plants were introduced, they may be assumed to have decomposed carbon dioxide, retaining the carbon and liberating the oxygen as at present. While a portion of this oxygen doubtless reunited with the vegetable matter on its decomposition later, the decomposing process was probably never complete, and a residue of free oxygen resulted. The oxygen of all the later periods is probably mainly derived from the decomposition of carbon dioxide by plant action. For the primitive atmosphere there is theoretical need for only enough oxygen to support the primitive plant life until it could supply itself, after which it would produce a surplus.

In the preceding discussion, the feeding of the atmosphere by the extrusion of the internal gases has been assumed. It is necessary now to consider how extrusive action might be initiated, and how maintained.

IV. The Initiation of Vulcanism.[1]

While some extrusion of the gases condensed within the rock-body of the earth may take place quietly and continuously, as the result of progressive contraction and of the rearrangement of material, and by means of diffusion and like processes, there is at present little or no observational ground for affirming that this is a process of much moment. It is, however, held to be such by some eminent geologists.[2] The recent discoveries of radio-active emanations from the earth and from ground-waters are at least interesting in this connection, though it is not now known what permanent contribution, if any, these emanations make to the atmosphere.

Vast quantities of gas are, however, shot forth by volcanoes, or more gently extruded from lavas. This is the chief demonstrable—as it is the only demonstrative—mode by which internal gases are given forth. It is by no means the universal opinion of geologists that these are really interior gases, coming for the first time to the surface (Vol. I, pp. 621–622, 633–636); but the accretion hypothesis assumes that this is the case for a large part of these gases, without excluding the participation of surface-water and atmosphere in producing some of the volcanic gases.

The sources of the requisite heat.

If it be granted that the growing body contained abundant atmospheric materials, the critical question arises whether an adequate degree of heat would be developed within the earth to actuate vulcanism and force the gases to the surface, when slow accretion is the mode of growth assigned. The sources of heat and the degree of their availability must, therefore, be considered.

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[1] Not improbably vulcanism was initiated before the gravity of the earth enabled it to hold an external atmosphere, as may be inferred from the phenomena of the moon, but it is more convenient to treat vulcanism after the sources of atmospheric material have been considered. In the main, the growth of the atmosphere and of the hydrosphere ran hand in hand with the development of vulcanism, under this hypothesis, and the precise order of initiation of the atmosphere and of vulcanism is immaterial. If the agencies of vulcanism did not bring it into action until after the earth acquired the ability to hold an atmosphere, the latter would begin to be collected from without.

[2] Suess, Geogr. Jour., Vol. XX, 1902, p. 520.

(1) **Heat from infall.**—The total amount of heat produced by the infall of the planetesimals would undoubtedly be more than sufficient to melt the whole mass, if the heat were all generated at the same instant; but if it were generated in successive moieties, spread over a long period, and generated at the surface where readily radiated away, no large amount might be retained, and high internal heat, such as required for vulcanism, might not be assignable to this source. In the present state of knowledge, the hypothesis may not unreasonably be given such a form as to make this source partially available, by assuming that in the early stages of accretion, while the nebular planetesimals were still relatively numerous, the collisions between them and the nucleus were so frequent as to make the latter hot. It is possible that mathematical inquiries, contemplated but not yet carried out, will show that this was probable, and that a rate of accretion so slow as to give a cool exterior would only come later, after the planetesimals of the feeding zone had been thinned out. But until that can be shown, the hypothesis must face the alternative possibility that the collisions did not succeed one another so rapidly as to greatly heat the growing earth-body by impact.

(2) **Heat from quasi-gaseous condensation of the nucleus.**—An unknown amount of heat may have been inherited from the nebular knot that constituted the original earth-nucleus. This knot is supposed to have consisted of an assemblage of small aggregates made from the heavy molecules of the nebular material; in other words, chiefly the metallic and the rock substances. This is held to be so because these substances would condense to the liquid and solid state at high temperatures, and further because, having low molecular velocities and relatively high gravity, they could assemble and remain associated by mutual attraction, while molecules of low weight and high velocities could not. These assemblages were probably rotatory or revolutionary, but perhaps rather irregularly so, somewhere midway between a well-organized planetesimal system and a heterogeneous gaseous or collision-rebound system, and combining some of the qualities of each. The ingathering of planetesimals from without probably tended to increase the irregularity, and to cause the assemblage to become more and more gas-like in dynamic nature. The matter being rock-substance or metallic, and hence partially inelastic, and the collisional velocities generally low, the mode of con-

densation was probably only in part analogous to that of a gas, but it is possible that an internal temperature not unlike that of a condensing gas might be developed. The young earth may, therefore, have inherited a hot nucleus.

(3) **Heat from central compression.**—The chief source of internal heat is, however, assigned to the progressive condensation of the growing body as material was added to its surface. The amount of this condensational heat for the full-grown earth, computed on the best data now available, is ample to meet all the requirements of the known geologic ages, as set forth under the subject of internal temperature in Vol. I, pp. 562–563. That heat arising from condensation *solely* would reach the melting temperature of rock in a body 1/20 of the earth's mass seems more or less doubtful; but in a body 1/10 of the earth's mass the required conditions would probably be reached. The requisite data are too imperfect for a definite decision of this point at present. If the pits of the moon (1/81 of the earth's mass) represent volcanic explosions, and not the infall of planetoids as Gilbert suggests,[1] it is necessary to postulate in its case conditions very favorable to the generation of heat by compression, or else to assign some notable portion of the requisite heat to the quasi-gaseous condensation of the nucleus, to the collisions of planetesimals, and to the source next to be considered, all of which would necessarily contribute something to the sum total of internal heat.

(4) **Heat from molecular rearrangement.**—Another source of heat lay in the atomic and molecular rearrangement of the material after it became entrapped in the growing mass. This was not simply chemical recombination, as usually understood, but molecular readjustment under pressure as well. The planetesimals were aggregated, by hypothesis, in a vacuum of the highest order, and with very slight mutual gravity, and the mode of molecular arrangement was that suited to this extremely low pressure. Under the rising pressure of the earth's interior, new arrangements of the molecules into denser combinations with lower specific heats are theoretically probable, if not inevitable, with the freeing of heat as a consequence. In a sense, this is a mode of condensation falling under the previous head, but it is not identical with mere mechanical compression, and is not wholly covered by computations based on compression.

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[1] Bull. Phil. Soc. Washington, Vol. XII, 1892, pp. 241–292.

The hypothetical mode of vulcanism. — With the detailed conceptions now developed, the method of volcanic action, deduced from the accretion hypothesis, may be readily apprehended, and the vital part which it began to play in earth-history may be realized. The chief portion of internal heat being assigned to compression, the temperature must have been highest at the center and must have declined toward the surface. By referring to pages 563–569, Vol. I, the distribution of pressures, densities, and temperatures for the adult earth will be found. These elements must have had the same order of distribution, in a general way, for any of the immature stages of the earth, but there should have been some differences in proportionate value because sources (1) and (2) named above would have become negligible elements as the earth grew to its maturity.

Melting due to outward flow of heat.—Pressure itself is probably incompetent to melt rock-substances that shrink in solidifying, but the high temperatures generated by pressure in the deep interior were constantly moving outward into horizons of lower pressures where the melting-points were lower. As the computed temperature at the center of the adult earth is about 20,000° C.,[1] there would seem to be no lack of heat, in the later stages at least. The essence of the problem lies in its redistribution and in its selective action. Its initial distribution and its outward flow have been set forth in the pages referred to in Vol. I.

Selective fusion.—The material of the interior was originally, by hypothesis, an intimate mixture of planetesimals of various kinds, with such gaseous material as they carried in, or entrapped, in the process of growth. This material, therefore, presumably ranged from the most fusible to the most infusible of rock-material that could take the form of aggregated planetesimals. As some of it was probably of the kind that shrinks much in solidifying, and some of the kind that shrinks little in solidifying, and some, possibly, of the kind that does not shrink at all in solidifying, it is probable that some of it was brought near or even to the melting-point by pressure, while other parts, intimately intermixed with these, were far from their melting-points. At any rate, the outward flow of heat, in such a mixture, must bring some parts to fusibility much before the melting-points of other parts were reached. Local spots of fusion must thus arise. To this fusion, the entrapped and occluded gases may be presumed to have contributed, and to have joined themselves to the fused masses, and to have aided in giving them fluidity.

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[1] A more elaborate discussion of internal temperatures due to compression, by Mr. Lunn, will soon be published under the auspices of the Carnegie Institution.

The dynamics of ascension.—As the rise of temperature continued, more and more of the mixed material reached the fusing-point, while other material so nearly approached it as to become plastic and permit readjustive movements. In this way, fused parts were permitted to join one another and to move in the direction of least resistance. The static pressure from the earth-body itself was always greatest below and least above, but was nearly constant for any given short period. The stresses arising from the differential tide-producing attractions of the sun and moon were also greatest below and least above, but were *periodic,* stress and relief following one another in semi-daily succession, giving a kind of kneading process (Vol. I, pp. 578, 579, and 629–632). These interior stress-differences are thought to have pressed the fused vesicles outward, causing them to unite and form threads or stringlets, which insinuated themselves through the more refractory portions that remained solid, and at length developed into tongues of some volume. As these liquid threads or tongues rose to higher horizons of lower pressures, and hence of lower melting-points, they carried with them a certain surplus of heat above that required to maintain their liquidity in the new horizon, and this surplus was available for melting or fluxing their way. They were at the same time, however, subject to loss of heat by contact with surrounding rock of lower temperature. They were thus, probably, at the same time taking up fusible material met in their path, and depositing old material as it became less adapted to remain fluid under the new conditions, either because it had reached the point of its saturation in the mixed rock-solution that had been developed, or had cooled to its point of congelation. The liquid thread was thus presumably taking on and giving up material continually as it worked its way outward, the process always being selective, and involving the retention of the more soluble or more fusible portions, and the rejection of the less soluble or more refractory portions. Since the included gases may be safely reckoned with the former class, there was a selective accumulation of these, and the ascending liquid became densely charged with them. To this ascensive process, those substances whose weight overbalanced the differential pressure, such as metallic iron and possibly the heaviest silicates, may be regarded as forming exceptions.

Arrested ascensions and attendant heating. — Theory does not require that these threads should all succeed in reaching the surface; indeed, it does not require that any should, in the initial stages, before compression had developed a great excess of heat in the central parts. The molten threads should simply rise until their excess of heat, their working capital, was exhausted, when they would return to the solid state and constitute tongue-like intrusions. In doing this, they would contribute heat to the tracts which they invaded. This, in addition to conduction, was a mode of conveying the intenser heat of the compressed central regions to the higher horizons, where the original temperature and the fusion-points were both lower. The failure of the earlier threads to reach the surface would thus be a means preparatory to the greater success of later ones. The conditions for penetration would probably be favorable up to the horizon where the temperature ceased to be higher than the surface melting-point. Below this the retention of the solid state was wholly due to pressure, the temperatures being above the surface melting-point. When the threads reached the higher zone, in which the temperature was appreciably below the surface fusing-point, the conditions were clearly adverse, and further ascent was dependent on a sufficient excess of heat, brought from below, to maintain the liquid state while this adverse tract was being traversed. It was probably also dependent on a fluxing power adequate to enable it to fuse its way through the solid zone of continuous rock that lies below the fracture zone. When it reached the latter, hydrostatic pressure and the inherent expansive force of its gaseous content would probably control its further course, in the main.

Now, having in mind that, at the early stage under consideration, the earth was growing, that its internal self-compression was increasing apace with its growth, that the heat was rising with the compression, that the temperature was highest at the center and graded towards the surface, that the heat was therefore always flowing toward the surface, and that it was also carried outward by the liquid threads, the succeeding steps may be followed easily.

Invasion of the fragmental zone and surface explosions.—The outer part of the young earth was made up of the recently fallen planetesimals and their fragments, and no doubt had a much broken, open texture. If there was, as yet, no atmosphere or hydrosphere, as in the case of the moon, there was no effective means for the washing of fine fragments into the interstices of the coarse, or, what is more important, for the solution of the material at the surface and the cementation of that below into a solid mass, as is the present habit on the earth; in other words, there was no effective healing process to unite the broken fragments. The porous clastic zone must, therefore, have extended downward to a depth at which gravity was able to force the fragments into continuity by its crushing effects. In a small body this zone would be deep.

When the rising lava-tongues reached this outer fragmental zone, fluxing was no longer required, as they could force their way by insinuation and by mechanical displacement. It appears almost certain that, in the upper part of such a fragmental zone, the interstices would make up a sufficient part of the volume of the aggregate mass to reduce its average specific gravity to a figure below that of the penetrating lava, even though the latter might be made up of lighter material inherently, and was also hot and liquid. The earliest tongues of molten material are supposed, therefore, to have generally lodged within the fragmental zone, taking various plutonic forms, as dikes, sills, laccoliths, and batholiths, and to have there given off their gases, which, more or less concentrated and condensed, doubtless not infrequently forced an exit to the surface by blowing away the overlying fragmental material (Fig. 32). The slight coherence of this material, the low gravity of the young earth, and the absence or scantiness of a resisting

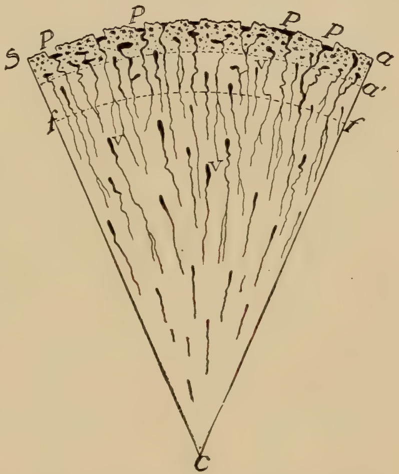

Fig. 32.—Ideal section of a portion of the early earth, illustrating its assigned modes of vulcanism. *C*, center; *S*, surface; *a–a'*, fragmental zone; *a'–f*, zone of continuous rock below surface melting temperature; *ff–c*, interior portion whose temperatures rise from the surface melting-point at *f–f* to a maximum at *C*; *V*, *V*, threads or tongues of molten rock rising from the interior to various levels, many of these lodging within the fragmental zone as tongues, batholiths, etc.; *PPP*, explosion pits formed by volcanic gases derived from tongues of lava below.

atmosphere should combine to give to the pit-forming effects extraordinary magnitude, such, perhaps, as the moon exhibits (Vol. I, pp. 597–598).

Volcanic action not necessarily antecedent to the atmosphere.—It is not necessary to the hypothesis to suppose that volcanic action was an essential preliminary to the acquisition of an atmosphere, nor that it came into function before the earth acquired an atmosphere, for the initial atmosphere may have been supplied from external sources. The apparent vigor and the wide prevalence of volcanic action on the moon, if its pitted surface means vulcanism, as well as the glassy material found in meteorites, whose origin is referred preferably to small atmosphereless bodies, favors the view that the internal gases were given forth abundantly before the earth grew to a mass sufficient to hold them. If this were true, an ample source of atmospheric supply was ready and waiting when the earth first acquired sufficient gravity to clothe itself with a gaseous envelope.

V. The Initial Hydrospheric Stage.

The origin of the ocean.—When the increasing water-vapor of the growing atmosphere reached the point of saturation, it took the liquid form and became a contribution to the hydrosphere. Probably condensation had occurred within the fragmental zone long before the external atmosphere reached saturation. The hydrosphere, therefore, probably had its birth underground, and so long as the fragmental zone retained its highly porous condition, it was what its name implies, a veritable sphere or spheroidal layer. As the water increased it rose to the surface, and doubtless first appeared in the innumerable pits resulting from the previous volcanic action, and in the depressions resulting from other deforming agencies. Its surface deployment is, therefore, pictured as a growth from innumerable lakelets, scattered with unknown promiscuousness over the face of the young planet, into more and more enlarged and confluent bodies, until at length they developed into the vast, irregular oceans of to-day. This evolution is of fundamental geologic importance, for it involves the origin of the ocean basins and of the continental platforms, and these constitute at once the grand topographic features of the globe, the great integers of deformation, and the controlling physical factors in the evolution of life. The evolution of the ocean basins and the continental platforms under this hypothesis is, however, exceedingly simple.

The evolution of oceanic basins and continental platforms.

With the acquisition of an atmosphere and hydrosphere, the conditions for weathering were present, and all those attendant processes of a gradational nature which constitute the dominant surface work of to-day, and which have been sketched at length in Volume I, were inaugurated.

Contrasted effects of weathering and protection by submergence.—For the present study, two features of these gradational processes overshadow all others: (1) *the weathering and leaching action on the land,* and (2) *the relative protection under the water-bodies.* The chemical changes wrought by the weathering of the surface of the land have been set forth in Volume I (pp. 41–43, 422, 426–430, 474–485). The essence is this: through the action of the atmosphere and atmospheric waters, the basic material is more largely dissolved and carried away than the acidic. When the weathering is thorough, the residue is chiefly quartzose sand—if the original rock contained quartz—and various residual earths and clays which are essentially silicious silts and aluminum silicates, with a low percentage of the basic oxides. If these earths and clays are turned back into crystalline rocks by metamorphism, they form acidic schists or gneisses, while the quartzose sand becomes quartzite. The material borne away in solution consists mainly of compounds of the alkalies and alkaline earths. A part of this is redeposited within the zone of the hydrosphere beneath the land, and a part is borne to the sea and remains in solution, or is deposited beneath it. Although some decomposition takes place in the zone of the hydrosphere beneath the land, and some also beneath the permanent water-bodies, it is clearly less than that which takes place in the zone of the atmosphere, and this difference in the sum total of work done, is all that need here be considered. There can be no question that the land areas lose by leaching, and the water areas gain correspondingly. *The general effect is an increase in the acidity and a reduction of the specific gravity of the land material.* This includes the land wash deposited on the borders of the continents.

Areal differentiation by selective action.—Now when the growing hydrosphere crept up to the surface and covered the lower tracts, a selective action of this kind began. The surface material of the areas that remained exposed lost more of its basic than of its acidic constituents, while the submerged material lost less, and perhaps gained something by the redeposition of the matter borne in from the land. As the planetesimals were being gathered in on land and water alike, those that fell on the land suffered some atmospheric change, while those that fell into the water were mainly protected from it. As this differential action affected each successive layer of growth after the accumulation of surface waters began, *the specific gravity of the land areas came to be less than that of the submerged areas.*

Permanent versus temporary effects. — It is not the temporary specific gravity that resulted from the change of physical state involved in disintegration that is to be considered here, but rather what may be termed the inherent or permanent specific gravity, i.e., the specific gravity that would be retained after any metamorphism which the material might probably suffer in the future had taken place. So likewise it is not the temporary chemical combinations arising immediately from the weathering, but the potential future combinations that are significant. For example, any rock likely to arise from the residual sands, earths, and clays by any probable metamorphism, or even by remelting, would have a lower specific gravity than the original average rock, or than any rock likely to be developed from the alkalies and alkaline earths removed by the leaching process in connection with the original rock. The leaching of the land material had, therefore, a permanent effect on its specific gravity, an effect not eliminated by any probable change resulting from its burial under later accumulations. The earth segments built up by accretion on the land were hence lighter than the segments built up under the waters, and the difference increased as the segments grew in thickness.

The progressive depression of water-covered areas.—It follows from the greater weight of the water-covered segments that the compression beneath them, as they became more and more weighted with incoming material, was greater than the compression beneath the land-segments, and hence the water-covered areas were depressed relatively more than the land-areas. The waters drawn in upon the depressed segments augmented the depressing effects due to difference in specific gravity.

It is not necessary to suppose that there was, at the outset, a general or continuous covering of certain large areas by water, and a general and continuous prevalence of land in other regions, but merely that over certain portions of the globe water-areas were more abundant than over other areas. Where water predominated, it may, at first, have taken the form of numerous small bodies. Such areas of prevalent water would, on the average, become heavier than other areas, and hence, acting more or less as units, would become more depressed. This excess of depression would extend the water-covered areas, and draw water away from areas less depressed, and this water would add its weight to the previous excess; and so, by progressive and cumulative action, develop the great water-areas and differentiate them from the chief land-areas. The tendency would always be toward the more complete unification of the land-areas and water-areas respectively.

So long as the earth continued to grow appreciably by accessions, the water-areas should continue to grow larger and deeper, and the

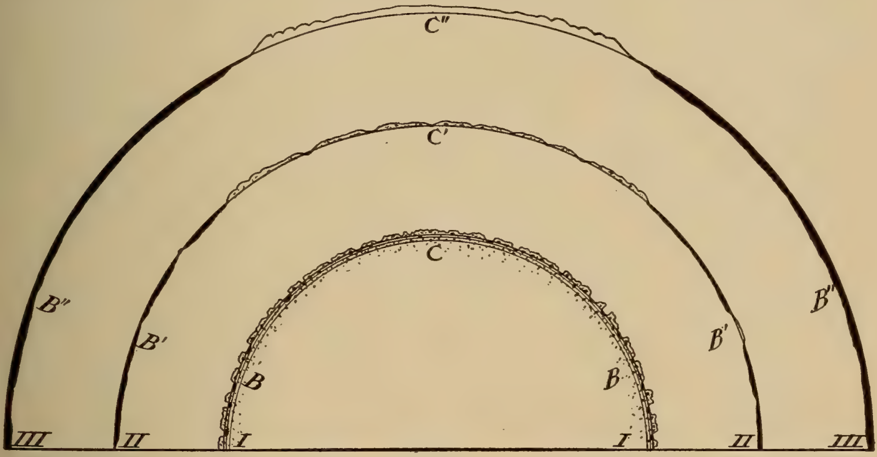

FIG. 32*a*.—Diagram intended to illustrate the evolution of the ocean basins under the planetesimal hypothesis. *I* represents an early stage in the evolution of the hydrosphere when it was largely subterranean, being held in the porous zone and only appearing at the surface in the volcanic pits developed by explosive vulcanism of the supposed lunar type. These are somewhat more abundant in the regions of *B B* than in that of *C*. *II* represents a more advanced stage in which the crater lakes of the regions *B*, *B* had become largely confluent, giving the interrupted water areas *B′*, *B′*, while the region *C* had become the more protuberant area *C′*, which was chiefly land. *III* shows the further progress of the aggregation of the water, the relatively greater depression of the oceanic basins, *B″*, *B″*, and the protrusion of the continent, *C″*.

land-areas narrower and higher, so far as this one process is concerned (Fig. 32*a*). The wash from the land tended to build its borders out into the water-basins, and other influences modified the results, but the deepening and spreading of the water-basins is believed to have been a markedly dominant process during the earth's growth. After growth ceased and modern processes became dominant, a more nearly balanced relation of sea and land is thought to have ensued, with a close approximation to constancy.

Configuration of basins accidental or systematic?—The amount of the original depression of the areas occupied by the water is assumed to have been slight, and, we prefer to think, accidental, so to speak. There may have been systematic causes that determined the relative depression of certain broad tracts and the relative elevation of others, such as some systematic difference in the infall, or some rotational change, or some inherent tendency to shrinking in certain particular ways, as for example that held by advocates of a tetrahedral earth;[1] but it is not clear that the actual distribution of depressions and elevations points to such systematic agencies. The elevated and depressed tracts of the moon seem to have a distribution quite unlike those of the earth, and those of Mars, if the lighter and darker areas are correctly interpreted as elevated and depressed tracts, are quite different from those of either earth or moon. Each seems to be a law unto itself, if such irregular distributions can be styled a law at all. Our hypothesis requires nothing more than the inevitable slight differences of growth, of volcanic activity, of compression, and their joint effects. Starting with only such slight differences as were sufficient to give preponderance in large tracts in favor of the water or of the land, the selective and self-propagating nature of the process may have done the rest.

Smallness of the differentiating action.—If it be assumed that the earth's growing hydrosphere appeared at the surface when our planet had attained the mass of Mars, whose radius is about 2100 miles, the subsequent growth would form a shell about 1900 miles thick. It is not altogether certain that Mars bears water-bodies on its surface, but the areas of greenish shade, environed by a surface generally ruddy, the polar white-caps ("snow-caps") that come and go with the seasons, and the apparent occasional presence of clouds, not to appeal to the evidence of aqueous absorption-lines in the spectrum reported by some good observers, but unconfirmed by others, lend some support to the opinion that water is present, though perhaps not in the form of definite water-bodies.

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[1] Emerson, Presidential Address. Geol. Soc. Am., Vol. II, pp. 61–106, 1900.

It has been inferred from the almost complete, and sometimes total, disappearance of the polar white-caps in summer, and from other phenomena, that the climate of Mars is phenomenally mild considering its distance from the sun. This has been regarded as all the more puzzling because of the scantiness of the Martian atmosphere, but it is what might be expected if Mars' atmosphere is like that assigned the earth when it had similar size, i.e., composed largely of the heat-absorbing carbon dioxide.

Without attempting to fix the precise stage, it is not unreasonable to assume that surface-waters had begun their accumulation upon the earth's exterior while yet it lay 1500 to 1800 miles below the present surface. The present difference between the radii of the oceanic basins and the radii of the continental platforms is scarcely three miles, on the average, so that if the continental segments be assumed to be in approximate hydrostatic equilibrium with the oceanic segments to-day, as seems highly probable, the selective weathering process brought about a difference in depression of only one mile in 500 or 600 miles, or about one fifth of one per cent. We appear, therefore, to be laying no heavier burden upon weathering than it is competent to bear. It might well be thought to do much more, but the process of weathering is very slow, and as new material was constantly falling in and burying the old, partial alteration was all that could take place; and besides, a part of the basic material leached from the surface was redeposited beneath the ground-water of the land, and was not lost to the continental segments.

Not only is the evolution of the great abysmal basins and of the continental platforms thus assigned to a very simple and inevitable process, but there is therein laid the foundation for subsequent deformations of the abysmal and continental type.

VI. The Initial Life Stage.

There is no direct evidence as to the time or the method of the introduction of life upon the earth. The earliest legible record of life, in the form of fossils, bears evidences of great advances in evolution along many divergent lines. The inference is, therefore, imperative that the initial forms of life had been introduced long before, or else that an evolution quite out of harmony with that which succeeded, took place in the unknown interval antecedent to the record. Whence the life was introduced is also quite unknown. The speculation that it might have been brought to the earth from some other celestial body by a fragment, in the form of a meteorite, is merely a refuge from supposed geological, biological, and philosophical difficulties—a merely temporary refuge in the face of prodigious improbabilities, for it only throws back the problem of life-genesis without solving it. There is nothing in known meteorites, save perhaps the existence of hydrocarbons equally assignable to inorganic sources, to indicate that they came from worlds with atmospheres and hydrospheres suited to maintain such life as the problem presents. On the contrary, there are the best of grounds for believing that meteorites came from bodies in which the essential conditions of life were wanting; for, besides the absence of free oxygen and water, there is an absence of the products assignable to weathering and to those rock-changes that spring from the presence of an atmosphere and hydrosphere. These embrace a large portion of all known rocks in the outer part of the earth, such as are characterized by quartz, orthoclase, the acid plagioclases, the micas, the amphiboles, etc. (Vol. I, p. 467), as well as the sedimentary rocks. The absence of these in the meteorites is peculiarly significant, because of their abundance in the earth. The hypothesis of the foreign importation of life encounters a special difficulty under the accretion hypothesis, in that *the planets were all forming at the same time.* Under the other hypotheses, the outer planets may have formed earlier than the inner ones, and an earlier evolution of life may have taken place in one of the older planets, whence a transference to the earth is barely conceivable. Under the accretion hypothesis even this is not a tenable refuge, and transfer from some other stellar system is the only obvious recourse.

Available time.—The accretion hypothesis affords an undetermined lapse of time between the stage when conditions congenial to life were first possible, and the stage when the first fairly legible record was made in the Cambrian period. To this unmeasured period the whole pre-record evolution of life, whatever be its method, may be referred, with every presumption that the time was ample, and there is no occasion for an evasion of the profound problem of life-genesis by referring it to some distant and unknown body. Nor is the problem vexed by duress of severe time-limits. A theoretical scantiness of time for a prolonged evolution previous to the Cambrian period has been deduced from a molten earth, but this does not apply to the accretion hypothesis. The supposed limitation of the sun's thermal endurance would apply if the arguments could be trusted, but their foundation has been cut away by recent discoveries (Vol. I, pp. 556–557). It is not the least of the virtues of the accretion hypothesis that it opens the way to a study of the problem of the genesis and early evolution of life free from the duress of excessive time-limits and of other theoretical hamperings, and leaves the solution to be sought untrammeled, except by the conditions inherent in the problem itself, which are surely grave enough.

The agency and the mode of genesis of terrestrial life are primarily biological questions, and as biology has, as yet, no solution to offer, these greatest of problems will not be considered here. The specially geological questions relate to the stage at which the requisite conditions for life were provided, to the special features of those conditions, and to the period available for evolution previous to the Cambrian records.

When were the conditions requisite for life first provided?—It is assumed that the conditions on which life is now dependent were prerequisites to its introduction. As already indicated, an atmosphere and a hydrosphere sufficient to sustain life may have been acquired when the earth was about the size of Mars, or one tenth grown. If, to be conservative, a preliminary growth of twice this amount be allowed, there still remains between this and the Cambrian record the growth of four fifths of the mass of the earth. So far, therefore, as atmosphere and hydrosphere are concerned, life may have been introduced early in the history of the earth, and may have had a vast interval for development previous to the earliest legible record. There is another essential condition, a sufficiency but not an excess of heat and light. If the formation of the parent nebula involved only the outshooting of a small fraction of the ancestral sun, the solar supply of heat and light may not have been so seriously disturbed as to have fatally affected its ability to furnish what was necessary for life at any stage of the earth's growth. The planetesimals between the earth and the sun, during the early stages before they were much swept up by the inner planets, may have screened off some appreciable part of the sun's heat and light; but the ratio of nebular matter to space was probably too small to render this loss critical. So long as the nebula itself remained luminous, the nebular light compensated in greater or less degree for the solar light cut off, but perhaps not for the heat. The nebulous surroundings of the growing earth must have somewhat reduced the loss of heat by radiation into space, and so have made some compensation.

Autogenic heat and light. — There was, however, a terrestrial source of heat and light of critical importance, namely, that arising from the infall of the planetesimals. If this infall were at a rate sufficient to heat the surface of the earth above 100° C., life of the present types would have been prohibited. The present stage of the inquiry does not permit any very confident opinion as to whether this excess was reached or not. Leaving this question open, it is to be noted that if, at the stage when first an atmosphere and hydrosphere could be held, the infall of planetesimals was so rapid as to heat the surface to a prohibitive temperature, the rate of infall must almost certainly have declined as the number of planetesimals in the earth's feeding-zone was diminished; so that, long before the supply was exhausted and growth ceased, the rate must inevitably have fallen below the prohibitive limit. If, therefore, the earth were too hot for life when one fifth grown, its temperature might have become suitably mild when one fourth, one third, one half, or three fourths grown. Growth after this permissive stage was reached would be slow, and the period required for its completion would still be long.

Transition to complete solar dependence.—In the early stages, the danger seems to be all on the side of too great heat. Even if the sun's heat were much less than now, the heat of planetesimal infall would probably make up the deficiency and more. The infall would continue to be a source of home supply so long as the accretion continued, declining as the supply of planetesimals diminished. This diminution of the supply cleared the space between the earth and the sun, and gradually brought the latter into full function. There would, therefore, be a gradual passage from the partial dependence on the home supply of heat and light, to complete dependence on the solar supply. There is little ground for apprehension that the infalling planetesimals would be seriously dangerous to the early forms of life, for, in the first place, the atmosphere must have been then, as now, an effective cushion checking the speed of the planetesimals and partially dissipating them, and, in the second place, the early organisms were probably all aquatic and were further protected by their water-covering.

Changes in the atmosphere inaugurated by the introduction of life.— The introduction of organic activity brought into play those chemical processes that have been sketched in general terms in Chapter XI of Volume I. The changes in the composition of the atmosphere are especially important. It has been shown (p. 97) that the primitive atmosphere probably contained a preponderance of carbon dioxide, and, a little later, carried all the water-vapor that it could hold under the prevailing temperatures, while the amount of nitrogen was not improbably low, and that of oxygen uncertain. If only there were oxygen enough to serve the functions of plant life at the outset, the existing large content of oxygen could probably all have arisen from subsequent plant action. It is merely necessary, therefore, to assume (1) that the carbon dioxide was not too abundant to prohibit the development of the early plants, (2) that the oxygen was sufficient for their vital processes, and (3) that the nitrogen was much less abundant than now, to give a good working basis for the evolution of the present very different atmosphere. Assuming that green (photosynthetic) plants were first introduced, and that, until some time later, there were no animals or predaceous plants that decomposed the carbon compounds produced by the green plants, the effect of plant life on the atmosphere would be to reduce its carbon dioxide and increase its free oxygen. If there were no check or offset to this process, a relatively short time would suffice for the conversion of an atmosphere of dominant carbon dioxide to one of dominant oxygen. If the present vegetation can remove the present content of carbon dioxide in one hundred years (see pp. 639–644, 645, Vol. I), an amount of carbon dioxide as great as the whole atmosphere of to-day might be changed to oxygen in about 300,000 years by an equally active vegetation. The early plant action may have been much less efficient than that of to-day, and the requisite period might be correspondingly lengthened, but it might still be geologically short. Besides, the early atmosphere, by hypothesis, was much less abundant than the present one, and probably much more active in the carbonation of rocks.

It is assumed that life requiring a high content of oxygen did not appear until after the composition of the atmosphere had been suitably changed in this way. After oxygen-consuming, carbon-dioxide-freeing organisms came into existence, the reciprocal action of the two classes of life tended to maintain an equilibrium, though not an equality, between the oxygen and the carbon dioxide in the air. At the same time, the carbon dioxide was continually uniting with the rock-substance of the outer part of the earth, as it does now, and was thus being removed from the atmosphere. The same is true of the oxygen, but probably then, as now, oxidation was less active and prevalent than carbonation. And so the combined result of plant life and of inorganic action was to bring down the content of carbon dioxide to a subordinate place. The nitrogen, being relatively inert, gradually accumulated and has now become much the most abundant constituent.

The great factors now all at work.

So soon as plants and animals had come into action, all the great factors potential in the earth's physical evolution were in play. Only the psychologic element remained to become a potential factor late in the history. But though all were in function, their relative parts were by no means equal, and the future stages were marked by the successive dominance of one or another leading agent. The first of these was the dominance of vulcanism.

VII. THE CLIMAX OF VOLCANIC ACTION.

By hypothesis, volcanic action only began some time after the beginning of the earth's growth, for it was delayed (1) by the lack of sufficient compression in the central parts to give the requisite heat, and (2) by the time required for this central heat to move out to zones of less pressure, where it would suffice to liquefy the more fusible constituents. But once begun, it gradually increased in actual and in relative importance until it reached its climax. This obviously came much later than the climax of growth, for it was dependent on the growth to give the increased compression from which arose the central heat on which the vulcanism depended. And so, owing to the sources of delay just cited, the maximum of volcanic action must have lagged much behind the accession of the material which remotely actuated it. It is, therefore, inferred that vulcanism continued to increase in activity long after growth had entered on its decline, and that there was an important period in which the dominant activity was volcanic.

The ratio of the volcanic products to the accessions and to the derivatives.—It is conceived that in the late stages of the earth's growth the amount of material poured out on the surface in molten form, or introduced into the outer parts of the earth from below, was very much greater than the accessions from without. Still later these declining accessions were so overwhelmed by the igneous extrusions that they became indistinguishable contributions. In this stage, too, it is held that the modifications wrought by the atmosphere, the hydrosphere, and organic life were also quite subordinate to the volcanic contributions. Disintegration is assumed to have gone little farther, usually, than to partially reduce rocks of the granitoid type to arkoses, and those of the basic type to wackes. Rather rarely, it is believed, was much pure quartzose sand, aluminous clay, or similar well-decomposed residuary material accumulated; rarely, also, much carbonaceous shale. Arkoses and wackes, when metamorphosed later, took on such a similitude to igneous rocks as to be more or less unidentifiable.

The Archean complex.—The formations of this period of volcanic dominance, with very subordinate clastic accompaniment, are regarded as constituting the Archean complex, though perhaps only the later portions of the great volcanic series are represented by the *known* Archean. Here, for the first time, we reach formations exposed to view, and observational geology begins to replace the hypothetical. As interpreted in the light of the recent studies in both the Old World and the New, the lowest accessible formations that can be given a place in the systematic series were originally surface lava-flows, attended by volcanic clastics in abundance, and by sedimentary clastics and chemical and organic deposits in quite subordinate quantity. Into these were intruded contemporaneously, and also at later stages of the same great era, enormous embossments of granite and other rocks. This intricate combination of surface flows, clastics, and intrusions, distorted, sheared, and metamorphosed, makes up the vast Archean complex.

Diastrophism accompanying the volcanic climax. — For obvious reasons the great climacteric era of vulcanism was attended by deformations of exceptional intensity. The transfer of so much material from below to the surface required a readjustment, while the intrusion of the enormous granitic batholiths of the Archean were in themselves a source of deformation. Great changes in the distribution of temperature were involved in the outward flow of the molten rock. This carried heat outward from the deeper zones, and expanded the rock in the zones through which the rising lava passed. There was, therefore, loss of both material and heat in the lower zones, and gain of material and heat near the surface, with the obvious effects. The principles set forth in Vol. I, pp. 564–568, relative to the general transfer of heat by conduction and its double effects were also in play. In harmony with this intensive combination of agencies, the Archean rocks, as we shall see in the next chapter, are extraordinarily folded and crumpled, and at the same time phenomenally traversed by intrusive sheets, tongues, and embossments of plutonic rock. Diastrophism probably had its climax with the climax of vulcanism, and both came, by hypothesis, about the time of the opening chapter of the *revealed* history of the earth.

It is at this stage, and with the great agencies thus related to one another, that we reach the lowest observable formations of the earth's body, in following the accretion hypothesis. It is for each student to judge for himself whether the postulated antecedents lead felicitously or otherwise into the actual state of things which the oldest known rocks reveal. The value of a hypothesis, when demonstration of its truthfulness is not yet possible, lies in its working qualities.

VIII. THE GREAT STAGE OF ATMOSPHERIC AND HYDROSPHERIC DOMINANCE.

To complete the survey of stages, it is necessary to glance forward through the remaining ages and note the great fact that, the growth of the earth having ceased, and volcanic action having passed its climax, the surface of the land was no longer subject to continual burial, but was exposed, age after age, to the action of the atmosphere and the attendant work of streams and ground-waters. The material removed by these agents was deposited in the basins. Throughout this stage, therefore, the dominant phase of geologic activity became the hydro-atmospheric or gradational, as nearly as it can be expressed or implied in a single word. Vulcanism and diastrophism continued to be very important accessories, but not the controlling factors. This stage embraces the Proterozoic, Paleozoic, Mesozoic, and Cenozoic eras, the chief portion of known geologic time.

Synoptical View of the Earth's History.

If we take a sweeping view of the stages of the earth's history from first to last, they fall into two great groups, with a transition period between them: *the stages of growth and the stages of maturity*, with an intervening transitional stage. In tabular form, and numbered in chronologic order, these stages appear as follows:

III. The Gradational Eon (Relative maturity)	11. The Cenozoic era		C. The better known eras.
	10. The Mesozoic era		
	9. The Paleozoic era		
	8. The Proterozoic era		
II. The Extrusive Eon (Transitional)	7. The Archeozoic era		B. The partially known era.
	(Under planetesimal hypothesis)	(Under gaseous hypothesis)	
I. The Formative Eon (Birth and adolescence)	6. The initial life stage	The initial life stage	A. The hypothetical eras.
	5. The initial hydrospheric stage	The congelation stage	
	4. The initial atmospheric stage		
	3. The initial volcanic stage	The molten stage	
	2. The atmosphereless stage		
	1. The nuclear or nebular stage.	The gaseous or nebular stage	

SUPPLEMENTARY CONSIDERATIONS.

I. The Differentiation of the Rocks during the Stages of Growth.

The general nature of the process by which the surface rocks of the continental areas were, by hypothesis, rendered more acidic and less heavy, has been set forth. To show more fully the bearing of the hypothesis on the general characteristics of the crystalline rocks, and on some of the outstanding problems presented by them, there is need to enter somewhat further into details, though the subject cannot be fully elaborated here.

The average original material.—If meteoritic material represents, in a general way, the average of the heavier and more refractory material of the siderial system, as seems probable from the fact that it comes from all quarters of the heavens and seems to represent almost as many different parent bodies as there are distinct meteoritic falls, it may be regarded as the type of what was the average earth-material in its *atmosphereless* state, if it had such state. If there be added to this a certain unknown proportion of the lighter and less refractory material that could not be retained in the gaseous state by a small body, the whole may be taken to represent the material of the full-grown earth. This addition would probably not remove the total average earth-material very far from the average of the meteoritic matter, and so, with some qualification, meteoritic matter may be taken as a rough, but somewhat too basic and metallic, standard of the total earth-material.[1] It is easy, however, to gain a false impression of the average nature of meteoritic material, for the stony meteorites are less readily detected than the iron ones, and hence a less proportion are recognized. Besides this, the stony meteorites usually disintegrate rapidly and soon disappear, and hence, if not found promptly, are not found at all. If, therefore, the meteorites that are averaged include simply those that are found, the result will be much too high in metallic material. The true average should include only those seen to fall. On this basis, Farrington concludes that the true average is represented essentially by stony material of the basic silicate type, with only a subordinate amount of metallic material, and that the average specific gravity is about 3.69.[2]

Volcanic differentiation.—It will be recalled that from an early stage, molten material is supposed to have been poured out on the surface at intervals, and buried by the infalling planetesimals. At the same time, the material was slightly weathered on the land-areas, and such of the material as was dissolved was carried into the water-areas. Later, when the surface had been sufficiently built up by accessions, this same material was exposed to a second possible volcanic experience, with further selective fusion and further surface differentiation. Still later, the process may have been repeated, perhaps again and again, for the first volcanic surfaces, may possibly have been as much as 1200 or 1500 miles below the present surface, and the number of possible repetitions of the volcanic round is large. A wide differentiation from the original state was therefore possible. As the last series of extrusions came after the cessation of appreciable accessions from without, *practically nothing but the various varieties of the differentiated product would appear at the surface.* That these should differ widely from the original average rock is not strange; but why they should differ in precisely the ways in which the surface rocks differ from the supposed average rock remains to be worked out, and the solution of this problem will, in some sense, be a test of the validity of the hypothesis. It is to be borne in mind that the result is not a mere selection based on the melting-points of the minerals found in the surface rocks, but is rather the outcome of a complex process of mutual solution and precipitation in which the modifying conditions of temperature, pressure, ratio of admixture, stress-differences, and specific gravities, play essential parts.

Differentiation in suboceanic versus continental segments. — It is reasonable to assume that the lavas which arose from the more basic segments that underlie the deep-sea basins would be more basic than those that arose from the more acidic land segments, and this seems to be supported by the greater prevalence of

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[1] For composition of meteorites, with references to the literature, see Farrington, Jour. of Geol., Vol. IX, 1901, pp. 393 and 522.

[2] Jour. of Geol., Vol. V, 1897, p. 130.

basic rocks in marine volcanoes. It is not to be lightly assumed, however, that differentiation may not develop acidic rocks from even the prevailingly basic magmas of the sub-oceanic segments. Volcanoes that arise from submerged ridges and platforms that were once land, are obviously not to be regarded as properly abysmal.

Obstacles to minute differentiation. — While in most respects the conditions postulated by the hypothesis were extremely favorable to the broader classes of differentiation, there were certain respects in which complete differentiation was hampered. One of the most notable of these was the apparent lack of a high degree of fluidity, and of a protracted condition of fluidity even of the more viscous kind. By hypothesis, the fluent material was developed by selective fusion from a mixed mass presenting all grades of fusibility, and hence there is little reason to suppose that any portion would become very highly fluent while surrounded by matter on the border of fluidity, or already viscous and ready to mingle with it. Moreover, the hypothesis postulates that as soon as any appreciable portion became mobile, it was forced toward the surface by the internal stress-differences, and in its outward passage was subject to loss of heat, as well as accessions and losses of material. Under all these conditions it seems most consistent to suppose that little more than viscous mobility—not perfect fluidity—was acquired. The matter is presumed to have been *in slow movement* upward from the time it acquired mobility, and the rising threads or tongues of lava were probably also subject to slow convectional currents, if at any time they reached a sufficient degree of fluidity to permit this. The portion next the cooler walls obviously tended to descend, while that in the central part tended upwards. Up to a certain point, a slow movement may be regarded as favorable to differentiation, by bringing together matter of the appropriate kinds. For example, it is probable that the growth of crystals is promoted by very gentle movement, just as it is probable that snow-flakes grow more rapidly by falling gently through moist air than they would if they remained in contact with the same air. But at the same time, motion must oppose the separation of the crystals from the moving mass, and by keeping them in it, lead to their final inclusion in the solidified mass. Between the high degree of viscosity and the appreciable amount of motion postulated, it appears that the individual crystals were not usually permitted to separate from the mobile mass by settling according to their specific gravities, and hence arose the complex mixture of crystals which is found in most igneous rocks, and which is so difficult to understand, if the lavas were perfectly liquid and remained quiescent in reservoirs while slow crystallization took place, for the heavier minerals often crystallized first. As the planetesimal hypothesis does not recognize any great reservoirs of molten material, standing for ages in a quiescent condition, the foregoing considerations relative to viscosity and to motion seem to meet the requirements of this puzzling phenomenon, at least in some degree. The specific gravities of the minerals common to igneous rocks vary rather widely, so much that the petrologist separates them readily by a series of liquids of graded specific gravities. The fact that they are not thus separated in nature in the case of rocks that have been lavas may prove a very significant phenomenon when its meaning shall be demonstrated. The climax of the phenomenon is found in the iron-bearing basalts of Greenland, in which little masses of the metal are scattered promiscuously through a stony base in meteoritic fashion, as shown in Fig. 32*b*. In this case the specific gravity of the metal is more than twice that of the embracing stony matter.

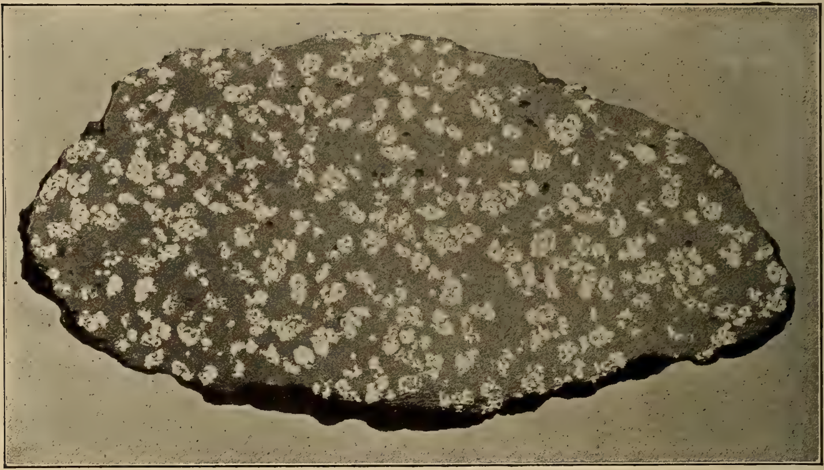

FIG. 32*b*.—A pronounced example of igneous rock composed of minerals of very different specific gravities that show no signs of separation by differences of gravity. The light portion is native iron, which has more than twice the specific gravity of the basalt, the dark portion, through which it is promiscuously scattered. From Kaersut, Nugsuaks peninsula, Greenland. (After Phalen, Smithsonian Misc. Coll., Vol. I, p. 199.)

II. DEFORMATIONS UNDER THE PLANETESIMAL HYPOTHESIS.

Relative to deformation two great eras are to be recognized, that of growth and that following the cessation of growth. During the stages of growth the chief cause of change of bodily form is assigned to the accession of material. This enlarged the geoid, and at the same time tended to compress it by the additional gravitative pressure. Heat arose from this compression, and, until it was dissipated, tended to prevent further compression. There was thus an antagonism between the opposing processes of growth and shrinkage, but during this era the former dominated.

When growth ceased to be appreciable, this type of diastrophism ceased to be dominant, but its effects were more or less perpetuated. In the subsequent era, the chief agencies of deformation are thought to have been a re-aggregation of material, with some extrusion, a re-distribution of heat in the interior, and a loss of heat from the surface. Incidentally there was some generation of new heat as in the previous era, but this is not presumed to have equalled the loss.

This twofold division of earth-history may be regarded as having given rise to three great stages of diastrophism, a first, in which accessions to the exterior, resulting in compression and heat, were dominant; a second, in which the transfer of molten material from the interior to the exterior, involving the transfer of heat, became dominant, this being the great volcanic stage that followed the main stage of growth; and a third, embracing the hydro-atmospheric eon, including most of the known geological history down to the present, in which diastrophism seems to have been dependent mainly on the re-distribution and loss of heat and the internal re-aggregation of material, and subordinately on the shifting of sediments. Obviously, these several stages were not separated by hard and fast lines, but rather graded into one another insensibly, and constituted merely successive phases of dominance.

The Modes of Deformation.

Reasons have already been given for believing that the water-covered areas would acquire higher specific gravity than the land areas, and would, therefore, take precedence in sinking, both in time and amount, and that thus the great basins and the continental elevations would arise. If deformations were limited to these greatest features of the earth's relief, the explanation might rest here; but their surfaces are still further diversified by plateaus, anti-plateaus, and folded mountains, as well as by the minor phenomena of faulted blocks, warped surfaces, etc. Some of these, as the folded mountains, especially when attended by overthrust faults, imply a compressive lateral movement (Vol. I, pp. 500–510); others, as the sunken blocks attended by normal faulting and gaping fissures, imply crustal tension (Vol. I, pp. 510–525). The problem therefore embraces not only the massive shrinkage supposed to have given rise to the abysmal basins and continental platforms, but such accessory actions as were competent to give rise to the plateaus, folded mountains, and lesser protuberances of a compressive type, and to inequalities of a relaxative type. (For preliminary discussion see Vol. I, pp. 542–589.)

The earth may be conceived to be formed of great sectors whose bases are the several ocean bottoms and continental platforms respectively, each constituting a cone, pyramid, or wedge, with its base at the surface and its apex at the center of the earth. Assuming these factors, for the moment, to be units of action, certain conceptions can be tested.

1. If the sub-oceanic and continental sectors all shrank in equable proportions in every part and simultaneously, the sectors would settle down within their own spaces and no unequal crowding would follow, and hence no crumpling. This is certainly not the actual case.

2. If the outer parts of all the sectors shrank proportionately more than the inner parts, each sector could not only have settled down within its own space, but could have permitted some tensional fissuring and faulting without involving lateral thrust or folding. This is certainly not the actual case.

3. If the sub-oceanic sectors simply contracted radially more than the continental sectors, to the extent of about 3 miles, the continental-oceanic reliefs

would have been attained, but the crumpling of the continental surfaces would be left unexplained.

4. If the sub-oceanic sectors sank first, for the reasons previously given, and, by virtue of their superior gravity, wedged aside and squeezed up the continental sectors between them, the continental surfaces would doubtless be warped and crumpled, and great reliefs and surface distortions be produced simultaneously. But would the *proportions* of lateral thrust and continental elevation accord with the facts? While it is necessary to recognize that no estimate of the total amount of lateral thrust involved in the mountain folding that has actually taken place is more than roughly approximate, we have previously taken 100 miles as a round figure representing the apparent order of magnitude of the crustal shortening due to folding since the pre-Cambrian times, on an entire circumference (Vol. I, p. 551). If, without change of volume, the continental sectors were squeezed proportionately throughout their mass by the sinking oceanic sectors, so that their surface breadths were reduced 100 miles, in the aggregate, on each circumference, they would be protruded several times as high as they actually are. It is obvious that this is not the whole of the actual case, though it seems to be a step toward it.

5. We have heretofore recognized the possibility that owing to the original distribution of heat in a self-compressing earth, the temperature may be still rising in the outer 800 miles or so of the earth, while it is sinking below, and that this may bring to bear special crowding in the outer parts (Vol. I, pp. 564–568). It may be, also, that crystallization has limits determined by pressure and heat, and that only a certain outer zone is crystalline while the central mass is in a miscible state, or in some unknown state of superior density. If this were true the outward distribution of heat and slightly increasing gravitative pressure might lead to the encroachment of this central mass upon the crystalline zone, by transformation from the crystalline to the miscible or other central state. This would result in a crowding of the crystalline zone on itself in the effort at adjustment to the shrinking central mass, in a manner analogous to the familiar crowding of the superficial crust on the shrinking subcrust. If in these, or in other and unrecognized ways, the outer parts of the sub-oceanic sectors be supposed to thrust the outer parts of the continental sectors relatively more than the central parts crowd one another, surface distortion, greater than in the previous case in proportion to the continental elevation, would result, and a nearer approach to the true case would be attained, but the proportions would still be wide of the true ones. But the *kind* of effect that would be produced in this way, normally, seems to suggest the source of a needed factor. If a segment, say 800 miles thick, were thrust against another segment of like thickness so as to shorten the latter 1 mile, with only negligible change of volume, the surface of the latter segment must be raised a mile over an area 800 miles in width, or its equivalent. Some change of volume by compression would be inevitable, but for the general conception here sought it may be neglected. Such crowding of thick segments seems to be of a kind suited to form plateaus, for the effect would probably be a swell or uplift whose breadth was more or less comparable to the thick-

ness of the distorted segment. The principles controlling the distribution of strains is thought to require this. Thinner segments should give plateaus of less breadth, and their heights should be determined by the extent of lateral thrust. In such cases, the crumpling at the surface would be small relative to the whole elevation. Some tension might even be developed on the top of the swell. Plateaus are commonly affected by much tensional faulting, but this may be due chiefly to the secondary action presently to be noted. They are also often affected by the more superficial distortions of the crust yet to be considered.

6. Under the hypothesis of a molten earth, it is agreed very generally that if a solid crust formed over the interior while the latter was hot and expanded, and that if the interior cooled and shrank later, the crust must have been too large for its contracted core and must have wrinkled to accommodate itself to it, involving horizontal thrust. If such a crust, whether formed in this or any other way, having a thickness of 20 miles, were thrust laterally 40 miles—Lesley's estimate of the amount of lateral movement involved in the folding of the Appalachian ridges in central Pennsylvania [1]—and folded into a mountainous tract 60 miles wide, and if the volume of the rock were preserved by upfolding, the average height of the upfold would be 13 miles, an amount which is quite out of accord with the facts. It is obvious on numerical inspection that no crustal thickness of this order of magnitude can give rise to the actual foldings with the actual elevation, if the approximate volume is preserved by upfolding simply. If preserved by infolding, which would probably be the normal mode in a floating crust, the result should probably be a synclinorium at the surface, with a very different expression from that which is actually presented. If the crust were mashed so as to give up-swelling in small part, and down-swelling in much larger part, a closer approximation to the real case might be made, but even then it is doubtful whether the configuration would be what it is.

With an earth solid throughout, whether from accretion or otherwise, no such disproportionate downward swelling is admissible. The thrust of a thick crust is competent to form a plateau, with some crumpling, but apparently not the requisite folding of the folded mountains with their limited elevations.

7. All hypotheses that postulate a solid globe, and perhaps all others, must apparently also postulate a shearing zone at a depth such that the amount of the lateral thrust correlated with the thickness of the thrust shell, shall correspond to the height of the folded tract, when suitable allowances are made for the compression and extension of the rocks, perhaps for some downward displacement, and for other incidental results, all of which are probably of small value. It is of prime importance to determine what this thickness is.

The thickness of the folded shell.—The thickness of the folded shell appears to be deducible from the extent of the thrust, as shown by the folds, combined with the average height and breadth of the folded tract. For example, if a thrust of 40 miles was involved in the folding of the Appalachian ridges in central Pennsylvania, as Lesley estimates, and if the highest fold was arched about 5 miles,[2] probably a rather high estimate, the average elevation of the folded tract before degradation may be taken at 2.5 or 3 miles above the previous surface, corrections for compression, extension, and possible downward thrust being neglected as immaterial for present general purposes. The present width of the folded tract is about 60 miles; its original width was therefore, by estimate, 100 miles. Now, a shell that has been crumpled from a width of 100 miles to a width of 60 miles, and in so doing has raised its surface 2.5 miles, on the average, must have been originally 3.75 miles thick, neglecting possible changes of density, etc. If it raised its average surface 3 miles, it must have been 4.5 miles thick, qualifications aside. A similar method may be applied to other mountain ranges for which approximate estimates of crustal shortening and of the heights of the folded area are available, and the results are of a similar order of magnitude. It appears therefore that the phenomena of the folded tracts themselves indicate that only a very thin shell was immediately involved in their formation.

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[1] 2d Geol. Surv., Penn. Summary, Final Rept., 1903, p. 206.

[2] 2d Geol. Surv., Penn., Pt. X, p. xxi, 1885.

The conclusion that a shell of a very few miles only was involved in the crumplings of the folded mountains is so important as to invite more careful estimates of the shortening of the crust, of the dimensions of the folds, and of the relative elevations of the folded tracts than have thus far been made, involving new and more critical measurements and perhaps new methods. Awaiting such improved data, a shell of perhaps 3 to 5 miles thickness may be taken as representative. This is found to be in reasonable harmony with other considerations. For example, a normal fold cannot well be less than twice the thickness of the folded strata until these have been closely recurved upon themselves and thinned by transverse pressure, and this only occurs when close appression takes place. A selection of the available cross-sections of the Appalachian folds mapped to scale in folios of the U. S. Geological Survey, measured liberally so as to include the lowest dips of the flanks, gives an average width of about 8 miles, or measured more closely so as to include the more distinctly folded portions only, about 6 miles. The halves of these fall within the range above given. The statistics of other mountain ranges, so far as available, are of similar import.

The shear-zone.—If we seek reasons for the limited thickness of the folded shell, and for a shearing-zone so near the surface, they may perhaps be found in the relations of the weight to the rigidity of the crust, or the ratios of weight to crushing-strength and shearing-strength. Available data as to the strength of rocks are very inadequate, and only tentative applications can be made. The experimental tests have usually related to the crushing-strength, rarely to the shearing-strength. They are also usually made on selected rock, well dried, and are hence probably higher than the average rock in its native wet condition. They are clearly higher than the native strength of rocks near the surface, where much weakened by fissuring, leaching, and other superficial changes. At moderate depths, however, these weaknesses disappear, and the rocks become practically continuous and sound. At greater depths, compression probably increases the strength, while increased heat tends to reduce it, but for the depths involved in this discussion neither of these factors probably becomes vitally important. The average crushing-strength of the granites that have been experimentally tested is about 25,000 pounds per square inch; that of the limestones about 16,000 pounds; and that of the sandstones about 6000 pounds; while that of shale, which has scarcely been tested at all, because unfit for building purposes, is appreciably less than that of sandstone. At the depths where the shearing-zone appears to lie, crystalline rocks undoubtedly exist in higher proportions than near the surface, and so the average ultimate strength undoubtedly rises toward the higher figure given, as the depth increases. It is to be noted, however, that among the crystalline rocks some have less strength than the granites tested.

Now, at a depth of a mile the vertical pressure arising from the weight of the overlying rock is about 6000 pounds per square inch, while the resistance of the rock to crushing is probably as great or somewhat greater than indicated above. At this depth, therefore, on the average, the weight of the rock will be insufficient to deform the crust by crushing, and thus adapt it to the shrinkage of the interior. The crust must meet the tendency of the interior to shrink away from it by a tendency to develop a parting, and thus bring into play the principle of the dome in its support, and thereby develop a tendency to lateral thrust. Now as previously shown (Vol. I, p. 581), the strength of even the best rock is utterly incapable of resisting the thrusts of the flat dome of the earth's crust when fully brought into play. At 3 miles depth the weighting has increased to about 18,000 pounds per square inch, at 4 miles to about 24,000 pounds, and at 5 miles to about 30,000 pounds. Within this range the weighting must approach, and perhaps pass the crushing-strength of the average rock involved. Down to the point where the weighting equals the crushing-strength, the tendency to arching with accompanying lateral thrust, must take precedence over the tendency to crush. At points appreciably deeper, where the weight is greater than the crushing-strength, deformation by flowage is the normal result. The distinction here is analogous to that between the zone of fracture and the zone of flow, as developed by Van Hise and Hoskins,[1] but is not strictly identical with it, for here lateral thrust and shearing-strength are essential factors. The zone of shear reaches higher than the zone at which fracture becomes impossible under radial stress alone. The zone of shear is perhaps identical with the lower part of the theoretical zone of fracture and the upper part of the zone of flow.

Folding in tracts of least resistance.—Now since the shrinkage of the interior is a slow and essentially simultaneous process, the shearing-stress probably develops an essentially simultaneous thrust over large areas, and as the shell offers much resistance to local folding, a conjoint shear for large areas—in distinction from numerous local independent shears—is developed, involving a common movement of large portions of the shell toward some tract of least resistance, where relief is found for the whole stress in a concentrated folding. Tracts of low resistance are obviously found (1) at or near the borders of the continents, where the crust is already flexed in its descent from the continental platforms to the ocean bottoms; (2) in tracts back from the borders of the continents where special flexures have been developed by deep sedimentation and attendant down-bowing; and

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[1] 16th Ann. Rept. U. S. Geol. Surv., I, 1894–95, pp. 589–603, 845–859.

(3) in tracts that have been weakened by previous folding or other causes. To initiate folding, the lateral thrust of the shell must not only become superior to the shearing resistance at its base, but also to the resistance of the beds in the weak tract to folding.

It must be confessed that the extent to which a common lateral shear appears to have taken place is greater than might have been anticipated from theoretical considerations. Shears for short distances only and moderate buckling at many points might have been expected, rather than shears of many miles affecting vast tracts by a common movement which concentrated their surplus dimensions in a single folded tract. It is perhaps not strange that the crust beneath each ocean basin should have thrust laterally from its center to its borders, where it was already flexed and weak, but the great concentration of the folding in most cases, and the fewness of the folded tracts in any given folding-period, seem to indicate that a conjoint movement of even greater extent took place.

Periodicity.—While the ulterior causes of folding may be supposed to be in continuous action, and hence folding liable to take place at various irregular times in different parts of the earth, and more or less continuously, the evidence of geologic history seems to indicate that there were long periods of accumulating stresses, followed by shorter periods in which the stresses relieved themselves by a rather general deformation of the several kinds indicated above. This view cannot be said to be held universally, however.

Supposed combined action.—From the foregoing considerations, the following conception of a typical deformation of the major order is deduced (Fig. 32*c*). Presuming, in accordance with the sketch of the stages of growth, that the oceanic basins and continental platforms have been determined previously, it is assumed that the transfer of material and heat in the body of the earth, the loss of heat from the surface, and, probably most important of all, the molecular re-arrangement of matter in the interest of greater density, gradually developed and accumulated stress enough to overcome the effective rigidity of the great mass of the earth, and to cause a general shrinkage. For reasons previously assigned, this is supposed to have been inaugurated in the sectors beneath the ocean basins, which are assumed to have shrunk radially, and to have crowded upon the adjacent sub-continental sectors to the extent of causing a slight relative increase in their elevations.

It is also to be assumed that, more or less locally or regionally, the upper parts of the oceanic and continental sectors, and perhaps subsectors, crowded specially upon one another for considerable depths and in varying degrees, and that these special deep-seated thrusts gave rise to the massive swellings that constitute plateaus. In neither of these cases, however, was the lateral thrust great, nor did it contribute much to superficial crumpling. It is assumed that the interior shrinkage involved the descent, relative to the center, of the continental sectors as well as the sub-oceanic, but to a slightly less degree. These continental sectors have been spoken of as being crowded up, or caused to swell up, implying elevation, in accordance with the common usage of terms in the literature of the subject. These terms relate to *the average level of the surface*, our most available plane of reference, not to absolute distance from the center of the earth. Rightly understood, these are proper terms, dynamically, since it is *the relation of part to part* that produces the distortional effect. There is a very closely related conception, which needs, however, to be distinguished from this, that of the shrinkage (settling) of the general crust away from certain portions, leaving the latter protuberant. Such areas, left above their surroundings by circumjacent depression, have been called *horsts*.[1] While the existence of horsts is not ques-

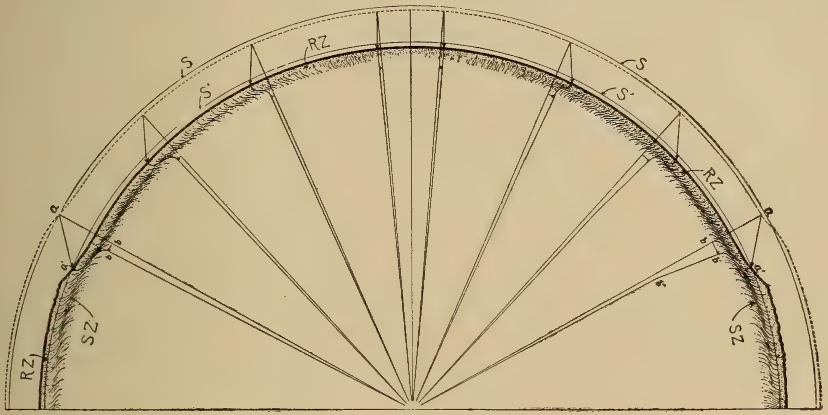

FIG. 32*c*.—Diagram illustrating the supposed elements of a general deformative movement. *SS* represents the outline of the sphere at the ocean level before deformation. The dotted line represents the corresponding surface of the lithosphere, the ocean basin occupying the center and the continents the flanks. *S′S′* represents the outline of the sphere at the ocean level after deformation, the heavy line representing the outer surface of the deformed lithosphere, and the space between *SS* and *S′S′* representing (much exaggerated relatively) the vertical shrinkage which is the great feature of the movement but is only made apparent through its deforming effects. That part of the outer shell which is beneath the ocean is supposed to descend without much compression, while the necessary folding is concentrated on the borders of the continent. The central portion beneath the ocean is represented as descending directly toward the center. The portions on each side preserve their length by thrusting laterally and hence descend along paths represented by the arrow-headed lines of which those at the border of the ocean *a*, *a′*, are the most oblique and represent the greatest thrust. On the borders of the continent the crust is folded to the extent of this lateral thrust. This of course only holds true when the thrust is limited to a single oceanic basin. The lateral thrust is chiefly felt in the outer shell or rigid zone, *RZ*, which embraces the heavy line and the dotted zone below. Beneath this lies the shear zone, *SZ*, whose foliated structure is represented as not unlike that of the "drag" belt of a fault plane. The igneous sheets, batholiths, etc., which are supposed to especially affect this zone, are not represented. The great sector beneath the ocean is represented as having crowded slightly upon the sectors beneath the continents on either hand, this crowding being represented by the short arrows *b*, *b′*. By comparing *bb′* with *aa′* the reason for the shear zone will be made apparent. On the right-hand side the outer part of the sub-oceanic sector is represented as crowding upon the continental sector an exceptional amount, as represented by the deflection of the line *b′b″*. This gives rise to the plateau at the right. The proportions of most of the significant parts are necessarily exaggerated relatively.

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[1] Suess, Das Antlitz der Erde, p. 167.

tioned, as will appear later, they are conceived to belong to a dynamical category different from that of the great plateaus here under discussion. In the formation of the latter, while the whole outer portion of the earth is supposed to have been descending, the plateaus included, *the parts mutually crowded upon one another*, resulting in the relative displacement of some of them by processes of wedging, squeezing, and mass distortion. The dynamics here were positive, so far as the parts were concerned, not negative, as in the case of true horsts.

The superficial shell, not having undergone the molecular and thermal changes assigned to the interior, and hence not having shrunk proportionally to it, is supposed to have accommodated itself to the shrunken interior by thrust, as previously described, and as commonly held under all hypotheses. Fig. 32*c* illustrates graphically the supposed movements acting conjointly.

The zone of accommodation. — Between the folded shell and the interior, where flowage-deformation prevails, there is presumed to be a zone of accommodation by which the one is adjusted to the other. This zone of accommodation is supposed to be affected partly by shear and partly by flowage, depending on the nature of the formations of which it is composed at any point, and on the nature of the stresses which there affect it.[1] It is presumed to graduate from shear along a few selected planes above, through shear along many planes in the middle, to continuous shear, or flowage, below, and thus to constitute a transition-zone from the shell to the main body.

The shear-zone a zone of foliation.—The more distributive phases of the shear in this zone would obviously give rise to foliation and schistosity. Structurally, therefore, the shear-zone becomes a zone of foliation, practically enveloping the globe next beneath the rigid shell. Under the planetesimal hypothesis, this zone is supposed to have been gradually lifted as the growth of the earth progressed, and hence to have undefined depth. In those portions of the continent that were protruded above the sea at an early date, and that were degraded to give material for the sedimentary rocks, it is conceived that this zone has been extensively exposed, and constitutes, in part at least, the foliated rocks now known as Archean; indeed the Archean areas are conceived to be essentially those portions of the shearing zone that have been brought to the surface by the removal of the shell that once overlay them.

The relations of the shear-zone to igneous intrusions. — From Fig. 32*c* it will be seen that the shearing-planes are flexed as a result of lateral movement, and that, typically, their section is a double curve, the middle portion of which may not be greatly removed from the horizontal. It is conceived that molten rock, on reaching this zone in its passage outward from the interior, would be predisposed to follow the shearing-planes already developed, these being the lines of least resistance. The rising molten rock must often have been solidified by cooling in the course of its passage, and hence residual portions arrested between the sheets of the shearing-zone may well be supposed to have given rise to that alternation of sheets of igneous rock and foliated rock which constitutes a common and typical phenomenon of the Archean terranes. It may well be supposed further, that the more viscous igneous rocks, by gradually stiffening, might often lodge in the more nearly horizontal stretches of the shearing zone, in large, flattened, disk-like lenses, and constitute batholiths. The enormous areas occupied by the Archean batholiths seem to find in this an explanation that does not involve the serious displacements of adjacent rock usually assigned to them.

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[1] Technically, flowage takes place by shear, but it is the shear of each part on every other adjoining part, while in the more common usage here followed, the shear is confined to selected planes.

Secondary or tensional movements.—In the foregoing primary deformations the movements are essentially compressive in effect. Incidentally, some tension is involved in particular portions, as on the tops of folds, and perhaps on the great arches of the plateau-swells, and elsewhere. These primary processes therefore offer no adequate explanation of the prevalence of tension in the outer part of the continents. As these tensional phenomena are widely prevalent, they imply a general cause. They are here referred to secondary action, following upon the primary deformation. In the sinking of the great sectors and in their mutual crowding, especially in the formation of plateaus, it is held that portions of the continent were relatively elevated above the plane of isostatic equilibrium, and, as the mass of the interior, though solid, is not absolutely rigid, there is ground for the presumption that the excess of gravity in the protuberant portions was gradually relieved by their slow sinking; in other words, a secular movement in the direction of isostasy would follow the periods of deformation. This view is especially applicable to the great plateaus. A direct movement downward, which would be the primary phase of an isostatic movement, would, however, tend to develop thrust, but because of the protuberance a lateral creep is postulated. Such a creep is postulated regardless of isostasy. The continents now rise about 3 miles above the average ocean bottom, and much more than that in certain portions. Since the volume of the ocean has probably not greatly changed during known geological time, and since the continents appear to have risen to and above the surface, about as now, in the earliest known geological ages, it is assumed that similar differences of relief have prevailed at the various known deformative periods. We have seen that the gravitative pressure at 3 miles depth is nearly or quite as great as the shearing-resistance at that depth. If a shearing-zone at depths of 3 to 5 miles had already been developed during the primary deformation, this would facilitate a reversed movement along the same shear-planes. It is therefore conceived that the continental platforms, by pressing upon their bases to the extent of 16,000 to 30,000 pounds to the square inch, would, though opposed by perhaps 5000 pounds per square inch pressure from the oceans, gradually creep laterally under their own gravity, in a slow glacier-like way. This supposed lateral creep should be attended by crevassing, fissuring, and normal faulting; in other words, *by the prevalent tensional phenomena which the continents present.* It should be much more marked in the plateau regions than elsewhere, because of their superior elevation, and it is there that normal faulting is most pronounced.

Horsts, rift-valleys, etc.—In a tensional movement of this kind, affected by various inequalities of bottom, of the shear-zone, and of resistance to creep, certain blocks of the shell may well be supposed to settle away from other blocks, leaving them protuberant as horsts. Certain other blocks might drop to levels lower than the adjacent ones, to fill the vacancy made by the spreading apart of neighboring blocks. Tiltings, rift-valleys, and other phenomena common to tensional areas would be natural accompaniments.

Relations to sedimentation.—Lateral creep from continental to oceanic areas should gradually lower the continents, particularly at their borders, and so induce a landward creep of the sea, giving rise to tracts of shallow water (epi-continental seas) well adapted to the shallow-water sedimentation which has prevailed in the continental areas during the course of known geological history. It should, furthermore, give rise to slight changes of elevation, by reason of the lateral movement over inequalities of base. Gentle warpings, undulations, and crevassings, should occur, as in glaciers, and for like reasons. Movements of these kinds, because of their extreme gentleness, would be admirably adapted to promote those common phases of stratification in which a nearly constant but slightly changing depth of water is maintained for long periods. The movement would also constitute an element in base-leveling.

On the borders of the continents, such supposed creep should give rise to several peculiar results that will be discussed under the Pliocene and later periods, since they seem to have specially manifested themselves at these times.

CHAPTER III.

THE ARCHEOZOIC ERA.

THE sketches of the early stages of the earth's history presented in the last chapter are at best only inferential, since they are not based on facts definitely recorded in any part of the earth's structure which is open to observation; yet they form, none the less, an indispensable preparation for the most intelligent study of that part of the earth's history which is recorded in accessible rock formations. As a brief résumé in a more concrete form, Figs. 33, 34, and 35, which represent diagrammatic radial sections illustrative of the different conceptions of the constitution of the earth's interior, are here introduced with the following summary:

1. According to the current conception of the history based on the gaseo-molten hypothesis (Fig. 33) there should be pre-sedimentary igneous or meta-igneous rock at all points below the prevailing surface sedimentary rocks. The plane of demarkation between these two classes of rock should be a sharp one, except in so far as obscured by the extrusions and intrusions of igneous rock which cross it, and by the infolding of sedimentary rocks in the lower mass. The fact that both the infolded sedimentary and the extruded and intruded igneous rocks may have become metamorphic, might make the separation of the pre-sedimentary rocks from the rocks of lesser age difficult, locally; but taken as a whole, the distinction should be recognizable.

2. According to the modified form of the gaseo-molten hypothesis, suggested in Chapter II (p. 88), there would be no sharp plane of demarkation between the original crust below and a dominantly sedimentary or meta-sedimentary series above, for between them there would be a zone composed of mingled igneous and sedimentary rocks, or their metamorphic equivalents (Fig. 34). This intermediate zone, in turn, might not be sharply differentiated either from the original crust below or the sedimentary group above.

3. According to the planetesimal theory, the core of the earth (Fig. 35) is made up of planetesimal matter, perhaps corresponding somewhat in composition to meteorites. After aggregation, the planetesimal matter was probably recrystallized under the influence of the heat and pressure which the aggregation involved, the resulting rock being essentially igneous in its nature. Outside the central core there should therefore be (1) a thick zone made up largely of planetesimal matter, but partly of igneous rocks erupted from below, and partly of sedimentary rocks. The planetesimal matter is assumed to predominate in the lower and major part of this zone; igneous rock, eruptive and irruptive, is assumed to have a somewhat irregular distribution within it; while the sedimentary rock increases in importance above, though remaining throughout a very subordinate constituent. This zone records the growth of the earth from the initiation of volcanic and atmospheric

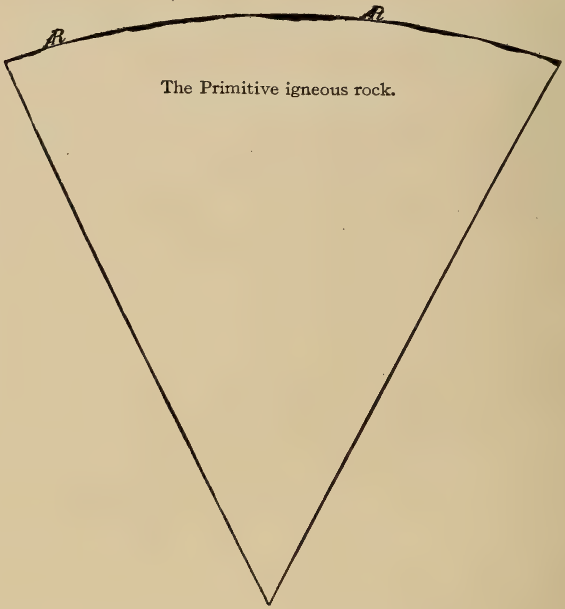

Fig. 33.—A diagrammatic sector of the earth illustrating its structure according to the Laplacian hypothesis. The great body of the earth is made up of the original igneous rock. Sedimentary rocks, together with some extrusive rocks, make but a thin coating, represented in the diagram by black, outside the great igneous interior. The original igneous rock is represented as appearing at the surface in some places (Æ). This, according to one view, might represent the Archean rock.

processes to the close of the period of notable growth by accretion. The central core and this thick zone about it represent the Formative eon (p. 119). (2) The next zone, probably a relatively thin one, is assumed to be made up dominantly of extrusive igneous rocks, with which would be associated subordinate amounts of sedimentary matter and matter

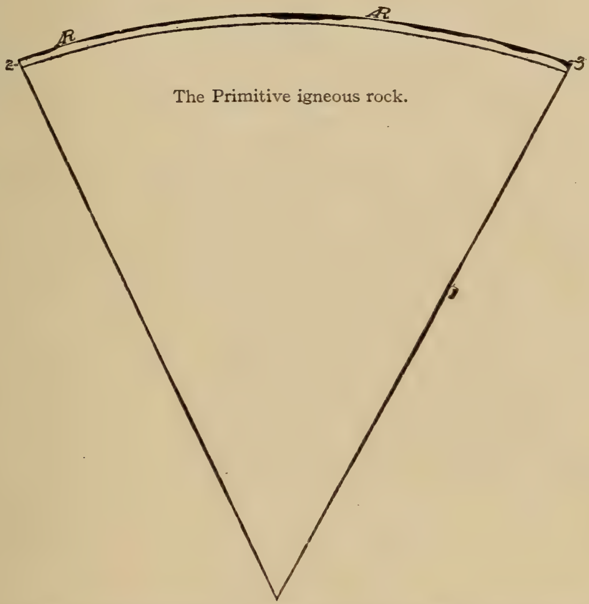

Fig. 34.—Diagrammatic sector of the earth illustrating its composition on the modified form of the Laplacian hypothesis. As in the preceding figure, the great body of the earth is made up of the original igneous rock. Outside this original igneous mass, there is, according to this hypothesis, a zone of extrusive material, with perhaps some sedimentary rock intermingled. This is represented by zone 2 in the diagram. The material of this zone is represented as coming to the surface at two points (AR). Outside this zone, there is a third zone made up primarily of sedimentary, but subordinately, of extrusive rocks. According to one interpretation, the material of the second zone might constitute the Archean rock.

gathered in from space. This zone represents the Extrusive eon (p. 119). (3) Outside it lies the superficial zone in which sedimentary rocks predominate, though associated with not a little rock of igneous origin. The first two zones outside the core are assumed to be universal, while the outermost zone, being composed primarily of material washed down from the land and deposited in the sea, fails to encircle the globe.

The oldest accessible formation.—With these ideal sections in mind, it is pertinent to inquire what might be the nature of the oldest rock formations accessible, on the various hypotheses which the diagrams represent. The deepest excavations yet made in the earth are but little more than a mile in depth, and while, by reason of upturning and erosion, rocks which once lay at greater depths below the surface have been exposed, the maximum thickness of rocks open to observation is but a few miles. Knowledge of rock formations and structures, based on observation, is therefore limited to some such thickness.

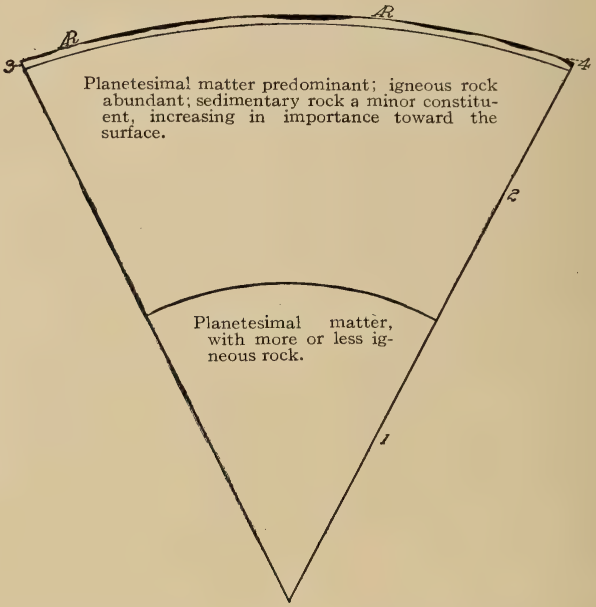
R
R
3
4
Planetesimal matter predominant; igneous rock abundant; sedimentary rock a minor constituent, increasing in importance toward the surface.
2
Planetesimal matter, with more or less igneous rock.
1

Fig. 35.—Diagram representing the structure of the earth according to the planetesimal hypothesis. The material of zones 1 and 2 is indicated in the diagram. Zone 3 of this figure corresponds to zone 2 of Fig. 34, and zone 4 of this figure corresponds to zone 3 of Fig. 34.

1. On the simpler form of the gaseo-molten hypothesis, we might hope to reach the original crust; for, considering the depths to which rocks are exposed, it is not rational to suppose that this crust, the principal source whence sedimentary rocks were derived, is everywhere covered so deeply by the derivative material as to be inaccessible. 2. According to the modified form of the gaseo-molten theory, the oldest accessible rock might not be lower than the deeper portion of the zone of mingled extrusive and sedimentary rocks intermediate between the original crust below and the dominantly sedimentary systems above.

3. On the planetesimal hypothesis, the oldest rocks to which we might hope to gain access would be those referred to the Extrusive eon (p. 119), during which more or less sedimentary rock was mingled with the volcanic. On this hypothesis, as on the preceding, no sharp line of demarkation would be expected between dominantly sedimentary rocks above, and dominantly non-sedimentary rocks below.

The rock-formations now most widely exposed at the surface are sedimentary, and were therefore formed during the time of atmospheric and hydrospheric dominance, that is, during the great Gradational eon (p. 119). In not a few places, however, formations of dominantly extrusive-igneous or meta-igneous origin are found, either beneath the prevailing sedimentary rocks, or projecting up through them in such relations as to show their greater age. In many cases these inferior rocks were thoroughly metamorphosed, and in essentially their present condition, before the deposition of the overlying beds, for masses of metamorphic rock derived from them are included in the non-metamorphic series above. These igneous and meta-igneous formations which antedate the oldest known series of rocks made up chiefly of sediments, are the oldest rock-formations known, and the era during which they were formed is therefore the first era of which there is definite record in the accessible formations of the earth.

These rocks consist of a very complex series of formations, embracing lava outflows, volcanic tuffs, igneous intrusions of various types and exceptional extent, together with some sedimentary deposits, all usually metamorphosed and notably deformed. Distinct fossils have not been found in these rocks, but the occasional presence of (1) carbonaceous shales very similar to younger shales which derived their carbon from organic sources, (2) iron-ore beds similar to those which owe their origin to plant action, and (3) occasional limestones and cherts which, as a class, are usually the products of organic action, are thought to imply the existence of life, and to warrant placing the era when these rocks were formed in the "zoic" group. This view is supported by the theoretical probability that life extended back through a vast period unrecorded by fossils, since the earliest fossils yet found imply a very prolonged antecedent evolution. The era during which, or during the later part of which, this oldest system of accessible rock-formation was made, is the *Archeozoic* era.

Under the planetesimal hypothesis, the oldest known rocks may be confidently referred to the Archeozoic era, for, according to this hypothesis, rocks of organic origin and rocks containing organic products were not only mingled with all series that are accessible, but with an indefinitely deep series below, since life is supposed to have originated long before the earth acquired its growth. The oldest formations known may also be Archeozoic under the modified phase of the molten hypothesis which has been presented (p. 88); but under the simpler form of the hypothesis of a molten earth, the original crust cannot be placed in the Archeozoic system, for its formation antedated the appearance of life. It must therefore be assigned to an earlier "azoic" or "lithic" era (see p. 83). Since recent investigations render it extremely doubtful whether any accessible rocks can be referred to the supposed original crust, there is little ground for referring any known rocks to an azoic era antedating the Archeozoic.

To avoid all difficulties arising from doubt as to the downward extension of organic rocks, the non-committal term *Archean* (Archean system, Archean complex) is commonly applied to the formations here referred to the Archeozoic era. This term is properly applicable to the oldest group of accessible rocks, whatever their origin, and whether contemporaneous with life or antedating its introduction.

Delimitations.—The lower limit of the Archean system is assumed to be inaccessible. Its *upper limit* has been fixed at different horizons by different authors. The term Archean (very old) was originally introduced to displace the older terms *Azoic* (without life) and *Eozoic* (dawn-life), whose etymological meanings made them sometimes inadmissible and sometimes of uncertain application. Originally the term was made to include all rocks below the abundantly fossil-bearing (Cambrian and later) systems; but progressive study has shown that there are three or more great systems of sedimentary or meta-sedimentary rocks (with interbedded igneous sheets), unconformable with one another, between the Cambrian sedimentaries above and the great complex of igneous and metamorphic rocks below. It has been thought by leading geologists especially engaged in the investigation of these formations, that the pre-Cambrian systems of dominantly sedimentary rocks should be separated from the dominantly igneous or meta-igneous complex below.[1] Following their lead, these pre-

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[1] Irving, Seventh Ann. Rept., U. S. Geol. Surv., pp. 448–454, and Van Hise, Bull. 86, U. S. Geol. Surv., pp. 491–493.

Cambrian systems of rock, composed chiefly of sediments, are here separated from the Archean, and designated *Algonkian* or *Proterozoic.* The former term is commonly used by members of the U. S. Geological Survey, and by some others, though it is little employed outside the United States. It has the same terminal form as Cambrian, Silurian, etc., terms applied to groups of strata of a much lower order of importance, and hence the term Proterozoic, corresponding to the terms of higher rank, seems a better name for the great group of systems between the Archeozoic below and the Paleozoic above. Since these systems are very thick and separated from one another by great unconformities, they represent a vast lapse of time, probably quite comparable in importance to that of the Paleozoic, Mesozoic, or Cenozoic, or perhaps even to all combined.[1]

There are theoretical reasons of some weight for separating from the Archean complex all series of rocks that are made up, in large part, of quartzose sandstones, mudstones, and limestones, or their metamorphic equivalents. These rocks are made up of the products of *mature weathering,* and therefore imply that the surface from which their materials were derived was long exposed to chemical decomposition *without very favorable conditions for wash;* otherwise partially decomposed products would have been carried away and deposited before decomposition was complete, and the result would have been arkoses and wackes rather than quartzose sandstones and shales. A covering of vegetation is the chief agency that now prevents this premature wash, and secures mature decomposition. While it may not be wholly safe to conclude that a vegetal covering of the land was a necessary condition for the formation of the quartzose sands and the muds which enter largely into the systems referred to the Proterozoic, it seems best to entertain this presumption to the extent of separating these systems from the more ancient complex of rocks in which the products of such complete decomposition do not seem to prevail. The term Archean is therefore here restricted to those formations, composed chiefly of igneous and meta-igneous rocks, which antedate the oldest known dominantly sedimentary system. Since the Archean system of rocks, as thus defined, is primarily of extrusive-igneous or meta-igneous origin, the era during which they were formed is, under the planetesimal hypothesis, regarded as the time of transition from the earlier *Formative eon* to the later *Gradational eon* (p. 119). According to the modified form of the gaseo-molten hypothesis also, the Archean rocks may be referred to the Extrusive eon.

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[1] Van Hise, Bull. 86, U. S. Geol. Surv., p. 491.

General Characteristics of the Archean.[1]

The Archeozoic era was characterized by great volcanic activity, as shown by the nature of the formations, and by great diastrophism and metamorphism, as shown by the deformations and alterations which the rocks had suffered prior to the Proterozoic era (Fig. 36). The rocks of no later era are so largely igneous, so notably deformed, or so highly metamorphic. Because of these characteristics, the interpretation of these rocks is difficult, and such views of their classification and correlation as are now entertained are to be held subject to emendation as investigation proceeds.

Subdivision.—Recent investigations seem to indicate that the oldest parts of the known Archean consist of altered surface flows of lavas, and pyroclastic rocks. This implies a preëxisting solid surface on which the flows took place, and therefore indicates that these are not the earliest rocks that were formed.

Associated with the metamorphosed surface lava-sheets and pyroclastic formations there are occasional beds of metamorphosed conglomerate and shale, and beds of jasper and iron ore, all of which imply contemporaneous water-action. Some metamorphosed limestones and sandstones are probably also to be included in the system. It is probable also that arkoses and wackes, produced by partial weathering and wash, are to be included. Such formations may have been abundant, though not now recognized, for after they are metamorphosed it is difficult to distinguish them from pyroclastic rocks and their metamorphic derivatives.

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[1] The Archean was formerly thought to be composed entirely of igneous and meta-igneous rocks; see Bull. 86, U. S. Geol. Surv., pp. 478–484, and 16th Ann. Rept., U. S. Geol. Surv., Pt. II, pp. 747–756. The character of the Archean as set forth in these publications needs some modification in the light of more recent discoveries. The sedimentary character of parts of the system is set forth in the following: Mono. XLV, U. S. Geol. Surv., pp. 129, 172–212; 21st Ann. Rept., U. S. Geol. Surv., pp. 317 and 402–404; Mono. XXVIII, U. S. Geol. Surv., pp. 186–188; Am. Geol., Vol. XXVIII, 1901, pp. 14–19; Jour. Geol., Vol. X, p. 71; Rept. of Bureau of Mines of Ontario, 1902, pp. 155–162; Geol. Surv. of Canada, Vol. III, Pt. I, F, 1887–99; Am. Jour. Sci., Vol. 50 (1895), pp. 58–60. Trans. Roy. Soc. Canada, 1899 and 1901. In the reference to Canadian localities, the rocks now classed as Archean (U. S.) are described under the name of Lower Huronian.

At a later stage there were great intrusions of molten rock into these surface formations, breaking them up and distorting and metamorphosing them in greater or less degree. It is not probable that the process of intrusion was distinctly separated from the process of overflow, but the intrusions, as we now find them, must have been preceded by the formation of the rocks into which they were intruded. To a phenomenal extent, the intrusions seem to have taken the form of massive batholiths, so that when the overlying rocks were cut away by erosion, as they have been since, the batholiths came to occupy large areas, and appear, on first study, to constitute a great formation by themselves. They were in fact so interpreted until recently, and seem to make up a large part of what has been called the *Laurentian* formation.

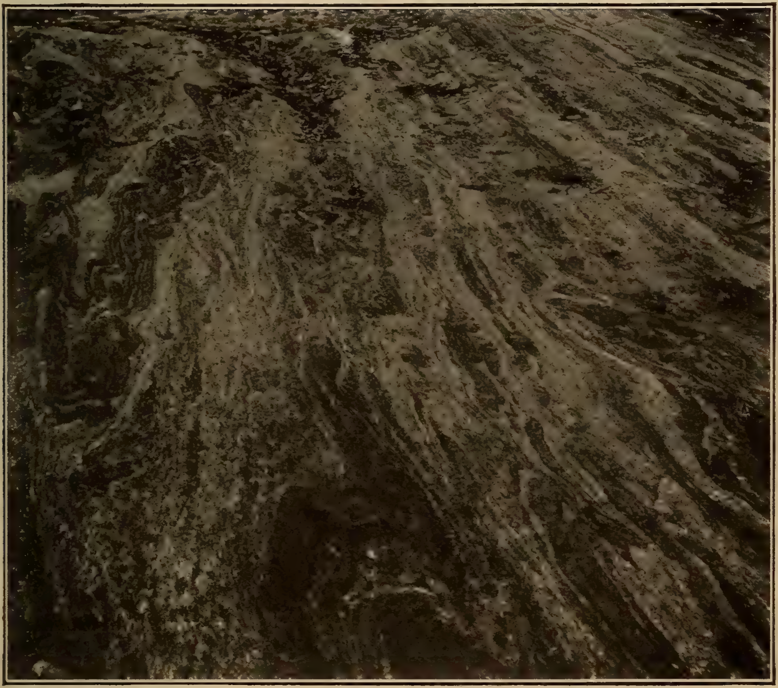

Fig. 36.—Figure showing the crumpled and contorted structure characteristic of much of the Archean rock. From a Canadian locality. (Ells.)

It is not improbable that the Archean is really much more complicated than this rather simple statement implies. Not unlikely, it consists of a much more extended succession of formations, reaching indefinitely downward, a succession such as might naturally arise during the processes of evolution sketched in the previous chapter. But at the present stage of investigation it is perhaps sufficient for a general view to recognize two great classes of formations as making up the definable Archean, viz., (1) a great schist series or group of series, and (2) a great granitoid series or group of series.

(1) **The great schist series.**—The schists of this series are the metamorphosed products of the lava flows, volcanic tuffs, and the included sedimentaries. The transformation involved both katamorphism and anamorphism; i.e., the lava-flows were mashed down into the schistose structure (metamorphism) and the clastics, while also pressed into the schistose form, were built up molecularly into a crystalline structure (anamorphism). In some portions, however, the original massive condition of the lavas is retained. In composition these schists and massive igneous rocks vary greatly, but since the most abundant material is of the neutral and basic types, the commoner metamorphic rocks are hornblende schists, greenstone schists, mica schists, etc. The local formations of the Lake Superior region, the Mona schists, the Kitchi schists, the Quinnissec schists, and the schists of the Keewatin, are regarded as members of this group. How far these and similar local series are equivalent, and how far they represent successive formations, it is not now possible to say.

(2) **The great granitoid series (Laurentian).**—Among the most conspicuous features of the regions of Archean rock, in their present eroded condition, are the great masses of granite and gneiss that commonly appear as embossments protruding through the schists, or as the country rock, over great areas. Like the schists, they are affected more or less by later intrusions. Until recently, these granites and gneisses were rather commonly regarded as the oldest known rocks. According to this view they constituted a basal formation, and so were styled "primitive" or "fundamental." The granites in particular were once quite generally regarded as portions of the original crust of the supposed molten globe. The associated gneisses and other foliated rocks, however, were sometimes regarded as the highly metamorphosed products of very early sedimentaries, supposed to have been derived

from the original crust under the peculiar conditions of a very hot, acid atmosphere. The granites and gneisses came to be widely known as the Laurentian formation, on the belief that they constituted a distinctive basal series; but it is now known, in many instances at least, that they are intrusions into the schist series. They are therefore younger than the latter. The gneisses are now regarded, in the main, as metamorphic rocks derived from granites by metamorphic action which mashed the massive rock down into the foliated condition.

In the formation of both the surface flows and the intrusions, the ascending lavas must have occupied numerous fissures or conduits connected with the interior, and hence there came to be numerous dikes and other forms of intrusions, traversing such parts of the Archean formation as had already been formed. It is also to be borne in mind that all subsequent igneous action required passageways for the lavas through the Archean, and that they also gave rise to traversing dikes and intrusions of later date. These later intrusions, many of them called Laurentian by Canadian geologists, are of course not properly of Archean age, but they are not always separable, and their presence adds to the complexity of the Archean as a whole.

Similar formations not Archean. — To avoid misapprehension, it is to be observed that granitic intrusions are not confined to the schist series above described. There are granitic embossments associated with younger systems of rocks; but it appears from present knowledge that such intrusions are much more local and incidental than in the Archean system, where they are so dominant as to constitute a leading and distinctive feature. It is also to be observed that there are, in various regions, great series of gneisses and schists, with associated massive crystalline rocks, which are not Archean at all, but metamorphosed portions of later formations.

A special characteristic feature.—A not uncommon feature in the American Archean is a series of numerous thin sheets of igneous rock a few feet or a few yards apart, which penetrate the gneisses or schists in directions more or less parallel to their foliation, giving rise to a coarse interleaving of later igneous and earlier foliated rock. This is so common as to be regarded by Van Hise as characteristic of the Archean, since it is not known to prevail in any later formation. These interleaved dike-sheets are commonly truncated at their junction with the overlying Proterozoic formations, which shows that they were formed not only before that series, but before the erosion which affected the Archean prior to the deposition of the base of the Proterozoic.

The diastrophism of the Archeozoic era.—It is probable that the intrusion of the great granitic masses was in itself a notable factor in the distortion which the schist series suffered, but it can hardly be assumed that the development of the schistose structure in great bodies of massive igneous rock was effected simply by the intrusion of lavas. Much less can the crushing down of extensive bodies of granite into gneiss be assigned to their intrusion in the molten state. The simplest and most satisfactory explanation of the prevalent foliated structure, of the interleaved igneous sheets and of the batholiths seems to be that previously suggested (p. 130), which refers all such structures chiefly to the shearing zone between the outer shell and the massive interior. If this be not entertained, some help toward an explanation is the conception that the extensive introduction of batholithic masses in the earlier series of surface formations, resulting in much disruption and distortion, would leave the whole in a condition well suited to develop extreme irregularity and intricacy of structure, whenever sufficient diastrophism was brought to bear upon the whole. Under these conditions, the included bosses of granitic rock would be peculiarly well situated for the development of the concentric schistose structure which is a common feature of the Archean system.

In still another way (p. 117) igneous action probably aided in the deformation of the rocks. The transfer of so much material from below, and its introduction into the outer parts of the earth, developed lateral pressure, not only by the intrusion and by the heat accompanying it, but also by causing the outer parts to settle down to take the place of the material transferred from below. The weight of the lavas spread upon the surface tended to the same end. The natural result would be lateral thrust in the outer parts of the earth, and this thrust would be relieved by the bending and crumpling of the rocks (Fig. 37), and by shear. Under the circumstances, this would be very irregular and intimate. Superposed upon this were the general forces of distortion which were operative with peculiar intensity in the earlier stages of the earth's evolution, as previously indicated (p. 122).

Metamorphism.—That the rocks should have undergone extraordinary metamorphism under the conditions described is most natural. It has been demonstrated that what were once massive igneous rocks have been crushed and sheared so as to develop a foliated or schistose structure.[1] It is in the rocks of this era primarily that metamorphism of this type is most commonly found. This is now regarded as having been a very extensive phenomenon, the larger part of existing gneisses, as well as a considerable portion of existing schists, having acquired their foliated structure by mashing and shearing. It is not to be overlooked, however, that some of the schists and perhaps some of the gneisses arose from clastic formations by anamorphic processes.

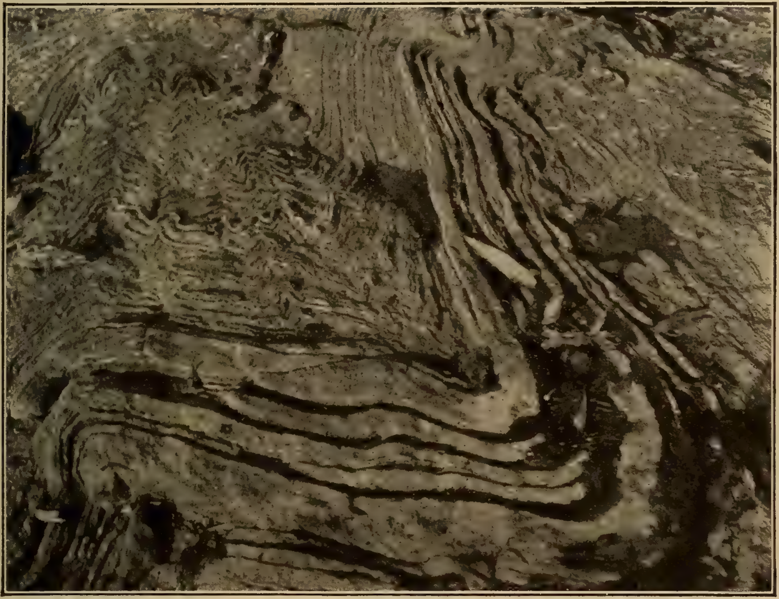

FIG. 37.—Figure showing the crumpled and contorted structure characteristic of much of the Archean rock. From a Canadian locality. (Ells.)

DISTRIBUTION AND LOCAL DEVELOPMENT.

General distribution.—The Archean is the one accessible rock system which is theoretically universal, in the sense that it underlies the whole surface of the globe. No later system does this. Wherever the Archean comes to the surface all later formations are absent, and some of them are absent elsewhere. In speaking of the distribution of a formation, it is generally understood, unless otherwise indicated, that its distribution *at the surface* is meant, and in speaking of its surface distribution, the mantle rock, glacial drift, etc., which overlie and conceal it are usually ignored, unless they are so deep as to make the underlying formation indeterminable. When the surface distribution of the formation is given, therefore, it is not to be understood that the formation is literally at the surface everywhere within the area specified, but that it is actually exposed here and there within that area, and that between the points of exposure it is the uppermost formation beneath the mantle rock. In this sense the Archean rocks are estimated to appear at the surface over about one fifth of the area of the land; but since much of Asia, Africa, and South America, and the less accessible portions of other grand divisions have only been reconnoitered geologically, this figure has only the value of a general estimate.

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[1] E. Emmons, Report of the Midland Counties of N. C., 1856; Lieber, Second Ann. Rept. on the Progress of the Surv. of S. C., 1858; Irving, Geol. of Wis., Vol. I., pp. 340–61; Adams, F. D., Rept. of the Brit. Assoc. for the Adv. of Sci., 1886; Williams (G. H.) Bull. 62, U. S. Geol. Surv. and Proc. Am. Assoc. for the Adv. of Sci., 36th meeting, 1887; and Van Hise, Sixteenth Ann. Rept., U. S. Geol. Surv., Pt. I. and others.

In North America,[1] by far the largest area of Archean rock lies in Canada. It occupies nearly the whole of the Labrador peninsula, and stretches thence in a broad tract southwestward to the line of the Great Lakes, and thence northwesterly to the Arctic ocean, east of the Mackenzie valley. This general statement is to be qualified by observing that formations of the Proterozoic era occupy numerous tracts within this area, and that many of them have not been separated from the Archean. A few small areas of still later formations overlie the Archean at certain points within this tract, but as the Archean underlies such formations at no great depth, the general statement made above is not seriously incorrect. This Canadian area is often likened to a great "V" or "U" with its apex resting on Lake Superior,

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[1] The literature on the Archean (as well as Algonkian [Proterozoic]) of North America was summarized by Van Hise in Bull. 86, U. S. Geol. Surv., in 1892. This publication gives full bibliography to its date. A later (1896) and briefer summary of the same subjects by the same author was published, Pt. II, 16th Ann. Rept., U. S. Geol. Surv., pp. 744–843. The pre-Cambrian literature since 1892 has been summarized from time to time by the same author, and by Leith, in the Jour. of Geol., as follows: Vol. I, pp. 304 and 532; II, pp. 109 and 444; III, pp. 227 and 709; IV, pp. 362 and 744; VI, pp. 527, 739, and 840; VII, pp. 190, 406, 702, and 790; VIII, p. 512; IX, pp. 79 and 441; and XII, pp. 63 and 161.

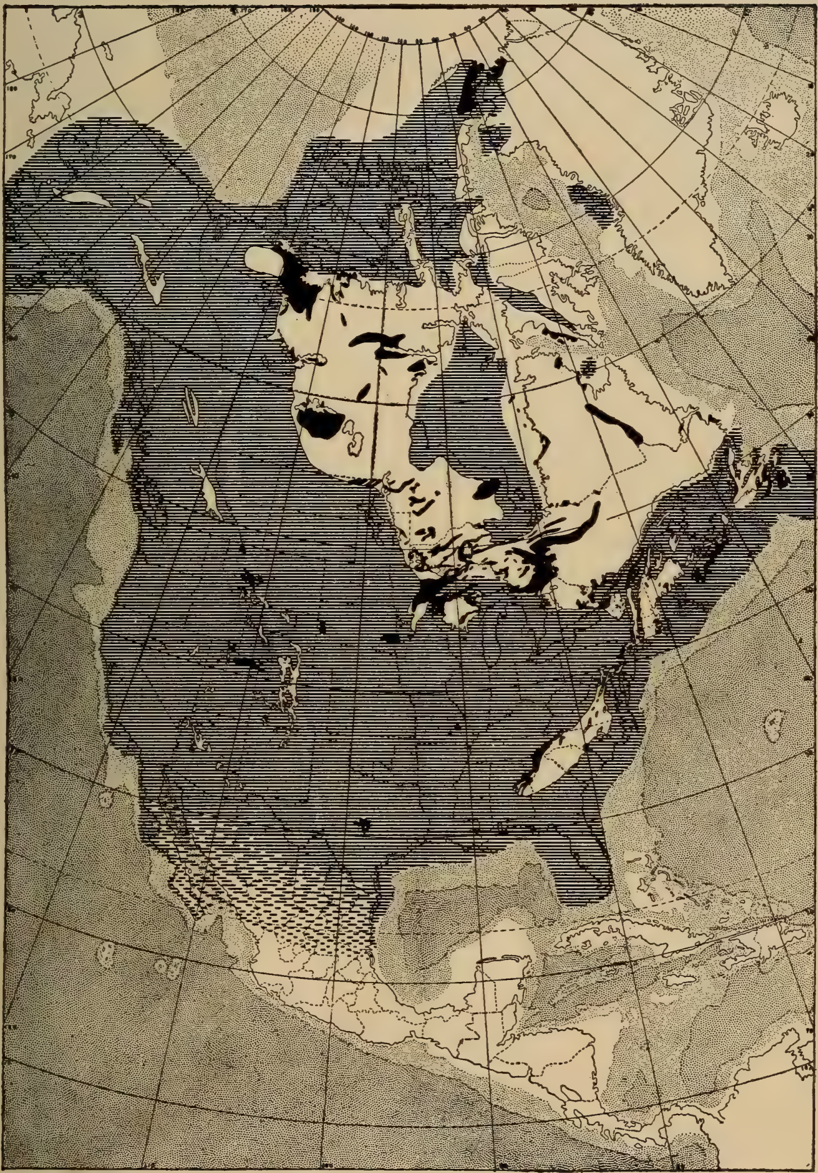

FIG. 38.—The white areas north of Mexico represent exposures of Archean with some undifferentiated Proterozoic; the white areas south of the United States represent lack of knowledge; the black areas represent exposures of Proterozoic, while the lined areas represent Archean or Proterozoic, beneath later formations. The light shading about the borders of the land represents the area of the continental platform covered by sea-water, or what is the same thing, the area of the epicontinental sea for this continent.

and its arms embracing the Hudson Bay basin, but the simile is not very accurate. The distribution may be seen in truer form and in greater detail on the accompanying map (Fig. 38), in which the white areas indicate Archean rock at the surface, the black areas Proterozoic rocks, and the lined areas either Archean or Proterozoic rocks underlying later formations. As indicated above, the Archean rocks are believed to underlie all later formations everywhere, but the lined areas of the map are intended to represent only those portions that are believed to have constituted a part of the continental platform, and not improbably were exposed at some time as land. It is to be understood that this map is no more than a rough approximation, representative of the present stage of mapping and interpretation. Closely related to this great Canadian area are tracts in Michigan and Wisconsin, in Minnesota, and in the Adirondack region of New York, though at least some of the rocks of this last region are probably younger (Proterozoic).

Lying rudely parallel to the great Canadian area on the southeast is a broken series of probably Archean tracts extending from Newfoundland to Alabama. Similarly, on the southwest side there is a belt of detached areas stretching from New Mexico to Alaska. In few places within these belts have the ancient rocks been studied in great detail.

Greenland, so far as can be judged from its known borders, is occupied by crystalline rocks of probable Archean age, and the same may be said of large tracts imperfectly known on the west side of Baffin bay.

Partly because of the inherent difficulties, and partly because of the inaccessibility of a large part of this great Archean tract, careful detailed work has as yet covered but a small part of it. The vicinity of Lake Superior in Canada, Michigan, Wisconsin, and Minnesota (Fig. 39), the original Huronian area north of Lake Huron, and the Ottawa region in Ontario, have been the classic areas of investigation.

Local development.[1]—A definite conception of the character of the Archean is best obtained by the study of its local development in typical regions that have been investigated in some detail. The following brief statements concerning the rocks of the system at selected points may be supplemented by the study of the original treatises referred to.

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[1] In addition to the references given in connection with the following paragraphs, the Archean appears on the maps of the following folios of the U. S. Geol. Surv.: *Arizona*, Globe and Bisbee; *Colorado*, Ten Mile, Anthracite-Crested Butte, Pueblo, Walsenburg, and Pike's Peak; *District of Columbia*, Washington; *Michigan*, Menomi-

In the *Marquette region* of northern Michigan, the Archean consists of (1) the *Keewatin,* Mona, and Kitchi schists (metamorphosed lavas and tuffs), with which are associated serpentines and dolomites (both derived in part from peridotites), and (2) the *Laurentian,* gneissic granite and more or less syenite, intrusive in the schists. These rocks are affected by numerous dikes and bosses of diabase, basalt, and granite.[1] A section showing the relations of the Archean to the Proterozoic rocks in this region is given in Fig. 40.

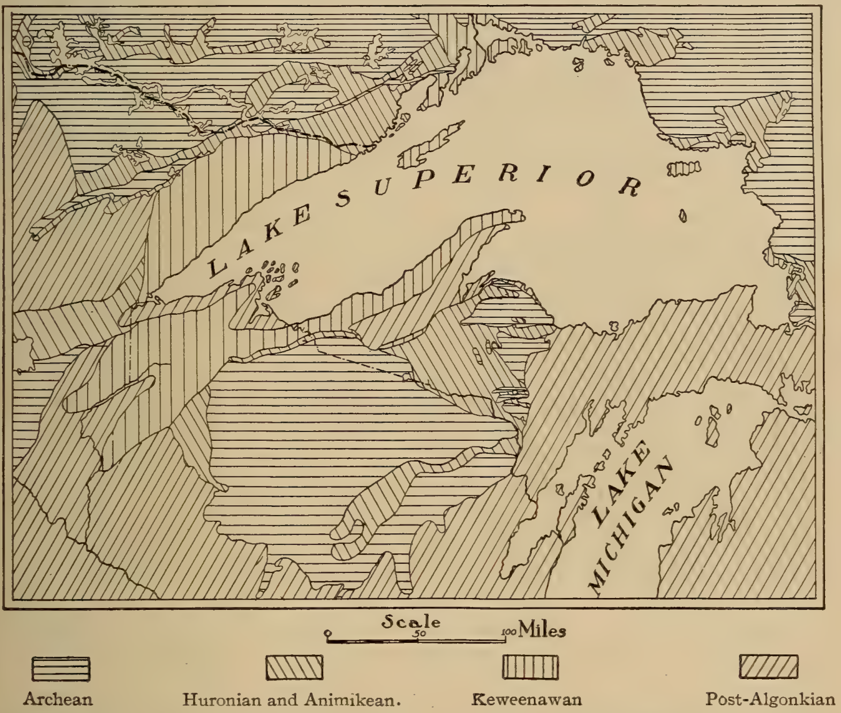

Fig. 39.—Map of the Lake Superior region showing the distribution of Archean, Huronian, Animikean, Keweenawan, and post-Proterozoic formations. (Van Hise and Leith, U. S. Geol. Surv.)

In the *Menominee region,* a little farther south, the Archean consists of (1)

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nee; *Montana,* Fort Benton, Little Belt, Three Forks, and Livingston; *North Carolina–Tennessee,* Asheville and Cranberry; *Tennessee–North Carolina,* Greenville; *Wyoming,* Absaroka and Yellowstone.

[1] Van Hise, 15th Ann. Rept., U. S. Geol. Surv., pp. 517–589, and Van Hise, Bayley and Smyth, Mono. XXVII, U. S. Geol. Surv.

Keewatin, greenstone schists and spherulitic greenstone, cut by dikes of gabbro, diabase, and granite, and schistose quartz-porphyry (Quinnesec schist) below, and (2) *Laurentian,* granites, gneisses, hornblende, greenstone, and mica schists above. The lower division is similar to the schists of the Marquette region, and represents metamorphosed igneous rocks of diverse origin (flows, tuffs, ashes, etc.).[1]

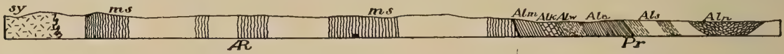

Fig. 40.—Figure showing the structure of Archean and Huronian formations in one locality in the Marquette region of northern Michigan. The Archean formations are: *sy,* syenite, and *ms,* Mona schist. The Huronian formations are: *Alm,* Mesnard quartzite; *Alk,* Kona dolomite; *Alw,* Wewee slate; *Ala,* Ajibik quartzite; *Als,* Siamo slate; and *Aln,* Negaunee formation (iron-bearing). Length of section, 3 miles. (Van Hise, U. S. Geol. Surv.)

In the *Mesabi district* of northeastern Minnesota[2] the Archean consists principally of various greenish rocks (*Keewatin*), including dolerites, basalts, diorites, micaceous and chloritic schists, with spherulitic structures common in the more massive portions, all of igneous or meta-igneous origin. With the greenstones there are some granites and porphyritic rhyolites.

In the *Vermilion district,*[3] the Archean consists of (1) *Keewatin,* the Ely greenstone, and the Soudan formation, and (2) *Laurentian* granites. The first is altered extrusive rock of andesitic and basaltic types. Locally they retain spherulitic and amygdaloidal structures, but they are largely schistose. The Soudan formation is meta-sedimentary, consisting of basal conglomerate derived from the Ely greenstone below, and an iron-bearing portion above. The latter consists of banded white chert, red jasper, carbonate-bearing chert, grünerite-magnetite schist, magnetite, pyrite, and hematite. Iron ore derived from the Archean is extensively mined in this region. The original forms of the iron were the carbonate and the silicate (sedimentary). Its change to iron oxide (chiefly hematite), and its concentration, as now found, were effected subsequently[4] (see Iron Ores, Chapter IV). The granites are intrusive in the Ely greenstone and the Soudan formation.[5] Figs. 41 and 42 show the relations

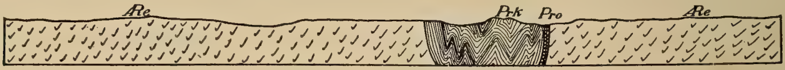

Fig. 41.—Figure showing the relations of the Archean and Huronian rocks at a locality in the Vermilion district. Archean formations: *Æe,* Proterozoic formations, *Pro,* Ogishkee conglomerate, and *Prk,* Knife Lake slates. Length of section, about 9 miles. (Clements, U. S. Geol. Surv.)

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[1] Van Hise and Bayley, Menominee folio, U. S. Geol. Surv.; also Bayley, Mono. XLVI, U. S. Geol. Surv.

[2] Leith, Mono. XLIII, U. S. Geol. Surv.; Winchell, Geol. and Nat. Hist. Surv. of Minn., Vol. IV.

[3] Clements, Mono. XLV, U. S. Geol. Surv.

[4] Van Hise, 21st Ann. Rept., U. S. Geol. Surv., Pt. III.

[5] Leith, Mono. XLIII, U. S. Geol. Surv.; Minn. Geol. Surv., Vol. IV, pp. 522–46.

of the several members of the Archean to one another and to the Proterozoic in certain parts of this region.

In the *Rainy Lake and Lake of the Woods districts* of Canada, the Archean consists of (1) *Keewatin*,[1] metamorphosed basalts, diorites, and other basic igneous rocks, associated with narrow bands of carbonaceous slate and limestone,[2] (2) *Laurentian* granites and gneisses intrusive into the Keewatin.

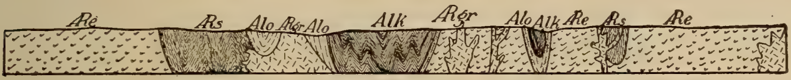

FIG. 42.—Figure showing the relations of Archean and Huronian formations in another locality in the Vermilion district of Minnesota. Archean formations: *ARgr*, Archean granite; *ARs*, Soudan formation; *ARe*, Ely greenstone. Proterozoic formations: *Alo*, Ogishkee conglomerate; *Alk*, Knife Lake slates. Length of section, about 5 miles. (Clements, U. S. Geol. Surv.)

The Archean complex, *Keewatin and Laurentian*, is also found on the north shore of Lake Huron, where it is overlain by pre-Cambrian rocks, chiefly sedimentary,[3] and again in the vicinity of Ottawa, where it is composed mainly of granitoid gneiss (Ottawa gneiss).[4] It is also known at various points about Hudson bay,[5] and between it and the Cambrian formation above there are two, and in some places three, great series of clastic rocks separated by unconformities. Throughout all this northern region the relations of the Archean to other formations are usually intricate.

The Archean in the great *southeastern belt* has been studied in detail in a few localities. In the vicinity of Washington,[6] D. C., the rocks classed as Archean include gneisses, schists, granite-gneisses, diorites and meta-diorites, gabbros and meta-gabbros, soapstone (altered peridotite and pyroxenite) and granite. Something of their relations is shown in Fig. 43. In an area of *western North Carolina*[7] where the rocks have been carefully studied, the Archean is divided into five or six formations, made up mostly of gneisses and schists (Fig. 44).

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[1] Lawson, Geol. Surv. of Canada, Vol. III, Pt. I, F, 1887–8, pp. 99, 100, and 105. Lower Keewatin = Ely greenstone and Soudan formation of the Vermilion region.

[2] Coleman, Bull. Geol. Soc. Am., Vol. IX, p. 224. Coleman considers the Lower Keewatin to correspond to the Lower Huronian (= Huronian of this Vol.), Rept. Ontario Bureau of Mines, 1900, p. 186.

[3] Logan, Rept. of Progress of the Geol. Surv. of Canada from its commencement to 1863. Bull. 86 and 21st Ann. Rept., U. S. Geol. Surv., Pt. II. Full bibliography given in Bull. 86, up to 1892. The 18,000 feet probably includes some Keewatin.

[4] This is the original Laurentian area. The rocks were formerly known as the Lower Laurentian. Logan, Rept. of Geol. Surv. of Canada, for 1845–46, pp. 40–51.

[5] See reports of Geol. Surv. of Canada.

[6] See references in Bull. 86, U. S. Geol. Surv.; and Keith, Washington (D. C.) folio, U. S. Geol. Surv.

[7] Keith, Cranberry (N. C.–Tenn.) folio, U. S. Geol. Surv.

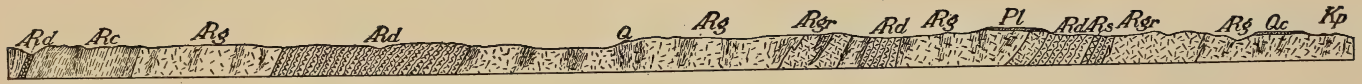

FIG. 43.—Section showing the relation of the Archean and younger formations in the vicinity of Washington, D. C. Archean formations: *Æc*, Carolina gneiss; *Ægr*, granite; *Ædr*, diorite; *Æs*, serpentine; *Æg*, gneiss. Younger formations: *Kp*, Potomac formation (Cretaceous); *Pl*, Lafayette formation (Pliocene); *Q* and *Qc*, Columbia formation. Length of section, 9½ miles. (Keith, U. S. Geol. Surv.)

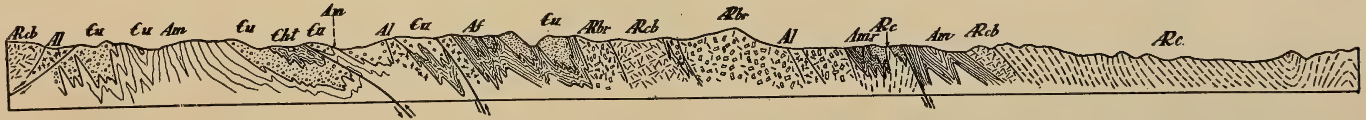

FIG. 44.—Section showing the relation of the Archean and Proterozoic rocks in western North Carolina. Archean formations: *Æc*, Carolina gneiss; *Æcb*, Cranberry granite; *Æbr*, Blowing Rock gneiss. Proterozoic formations: *Al*, Linnville metadiabase; *Am*, Montezuma schist; *Af*, Flattop schist; *Amr*, metarhyolite. Younger formations: *€u*, Unicoi formation (Cambrian); *Cht*, Hampton shale (Cambrian). Length of section, about 20 miles. (Keith, U. S. Geol. Surv.)

Some members of the series are clearly intrusive in others, and therefore younger. The older members show profound metamorphism. In the older formations a first dynamic movement developed foliation in rocks which were originally igneous, while a second folded the planes of foliation. Two profound metamorphic movements are thus recorded.

The Archean of the great western belt has similar characters. In the Grand Canyon of the Colorado, in northern Arizona, the same types of rock (the Vishnu terrane [1]) are exposed. They are separated from the Cambrian by the Grand Canyon system,[2] itself divisible into two series by an unconformity,[3] the upper being unconformable below the Cambrian.

The relations of the Archean at various other points in the west are illustrated by Figs. 45 to 48.

The structure of the Archean system is usually more complex than would be inferred from any brief descriptions, such as those given above. It would indeed be difficult to obtain an exaggerated idea of the complexity of the relations of the various sorts of rock which have caused this system to be called variously the "Archean complex," the "basement complex," the "fundamental complex," etc.

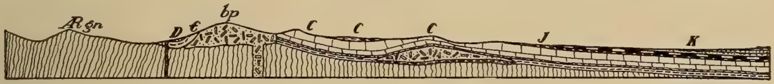

Fig. 45.—Section showing the relations of the Archean to other formations near Fort Benton, Montana. *ÆRgn*, Archean gneiss; *Ꞓ*, Cambrian; *D*, Devonian; *C*, Carboniferous; *J*, Jurassic; *K*, Cretaceous; *bp*, Barker porphyry. Length of section, about 21 miles. (Weed, U. S. Geol. Surv.)

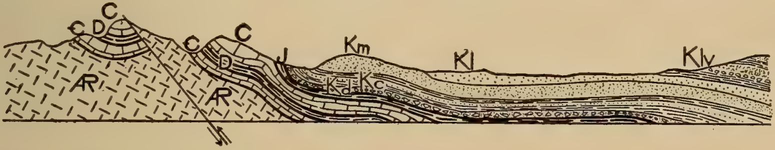

Fig. 46.—Section showing the relation of Archean to younger formations near Livingston, Montana. *ÆR*, Archean; *Ꞓ*, Cambrian (Gallatin limestone); *D*, Devonian (Three Forks shale and Jefferson limestone); *C*, Carboniferous (Madison limestone and Quadrant quartzite); *J*, Jurassic (Ellis formation); *Kd*, *Kc*, *Km*, *Kl*, and *Klv*, Cretaceous (Dakota, Colorado, Montana, Laramie, and Livingston, respectively). Length of section, 11 miles. (Weed, U. S. Geol. Surv.)

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[1] Van Hise, Bull. 86, U. S. Geol. Surv.; and Walcott, 14th Ann. Rept., U. S. Geol. Surv., Pt. II, p. 506.

[2] Powell, U. S. Geol. Surv., and Geog. Surv. of the Territories; Rept. on the Geology of the Eastern Portion of the Uinta Mountains, 1876, p. 70.

[3] Walcott, 14th Ann. Rept. U. S. Geol. Surv., Pt. II, p. 506. The Vishnu of Walcott appears to be Archean, leaving only the Unkar and the Chuar divisions of the Grand Canyon series between the Archean and the Cambrian.

By way of summary it may be said that the system consists in some places of rocks which are mainly massive (igneous); in other places, of rocks which are mainly gneissic (chiefly meta-igneous); and in still others, of rocks (largely meta-igneous and subordinately meta-sedimentary) in which a schistose structure predominates. Furthermore, the rocks of each of these structural types have a wide range in composition, from acid on the one hand to basic on the other. Rocks of all these classes are often intimately associated, and any one may predominate over the others to varying extents. In some places the rocks of these several structural types graduate into one another so completely as to leave no line of separation, while in others their definition is sharp. Thus massive rock sometimes appears in well-defined dikes which cut the gneisses and schists at any angle, while on the other hand, schists are frequently in dike-like sheets in rocks which are more massive. In the first of these cases, the gneissic or schistose rock which incloses the dikes of massive rock probably suffered metamorphism before the intrusion of the latter, which has never been changed; in the second, the inclosing rock was not metamorphosed before the intrusion, and in the changes of subsequent time the intrusive rock

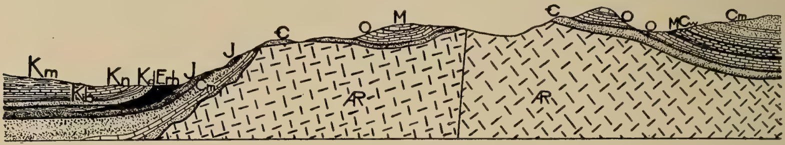

Fig. 47.—Section showing the relations of Archean to younger formations in the Crested Butte region of Colorado. *Æ*, Archean; € Cambrian (Sawatch quartzite); *O*, Ordovician (Yule limestone); *M*, Mississippian (Leadville limestone); *Cw* and *Cm*, Carboniferous (Weber and Maroon formations, respectively); *J*, Jurassic (Gunnison formation); *Kd*, *Kb*, *Kn*, and *Km*, Cretaceous (Dakota, Benton, Niobrara, and Montana, respectively); *Erh*, Eocene rhyolite. Length of section 6 miles. (Eldridge, U. S. Geol. Surv.)

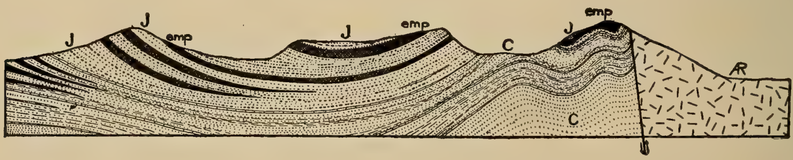

Fig. 48.—Section showing the relation of the Archean to younger formations in the Ten Mile district of Colorado. *Æ*, Archean; *C*, Carboniferous; *J*, Jurassic; *emp*, Elk Mountain porphyry. Length of section, 4 miles. (Emmons, U. S. Geol. Surv.)

was the more altered. Furthermore, the relations of these several sorts of rock have been enormously complicated by the distortion to which they have been subject. The structure and relations of the several sorts of rock in the system indicate that it was (1) by successive intrusions, large and small, of rocks of different chemical composition, into (2) still older rocks which were originally (*a*) chiefly extrusive-igneous and of varying chemical composition, but (*b*) subordinately sedimentary, and (3) by successive dynamic movements resulting in various degrees of metamorphism and deformation of the various parts, that the intricate structure and composition of the Archean complex was attained.

While, therefore, the variations in the rock of the Archean complex are great, there is, nevertheless, a certain homogeneity in the heterogeneity of the whole. No one considerable part of the system is very different from any other considerable part, and no definite and orderly relationship between the different parts has been made out over any considerable area. There appears to be no traceable succession of beds, and no definite stratigraphic sequence, such as can be made out in great series of meta-sedimentary rocks, however much folded and metamorphosed. So similar are the rocks of the Archean throughout the various areas where the system occurs, that a suite of unlabeled specimens from one region could hardly be asserted not to have come from any other.[1] This striking similarity affects not only the general features of the rocks concerned, but also many of the details of their structure and composition. The minerals of which they are composed everywhere (broadly considered) give evidence of having been subject to great dynamic action. They are often broken and distorted, and microscopic study reveals the effects of dynamic action in many cases where it is not visible to the unaided eye. The mineralogical and chemical constitution of the series, taken as a whole, appear to be essentially constant, in the sense that the variations in any one area are very much the same as those in any other.

Bearing of the Archean on the theory of the origin of the earth.—If any accessible system of rocks can be made to throw light on the origin and early history of the earth, it is the Archean. With the essential facts concerning the constitution and structure of the system in mind, it is in order to inquire to what hypothesis of the earth's origin they best adjust themselves. The constitution of the system makes it clear that it does not represent the original crust of the earth or its downward extension. It cannot be affirmed, however, that no part of what is now classed as Archean is referable to the original crust; that is, it cannot be affirmed that no part of the igneous or meta-igneous rock of the Archean is referable to an azoic or pre-zoic period, strong as the evidence against such reference may seem. On the other hand, all the facts now known concerning the Archean adjust themselves to the planetesimal hypothesis, or to the modified form of the gaseo-molten hypothesis. They cannot, however, be said to establish either, or to preclude other hypotheses of the origin of the earth. The question of the origin of the Archean must, therefore, still be regarded as an open one. According to the planetesimal hypothesis, the Archean is looked upon as representing the time of transition from the earlier Formative eon to the later Gradational eon (p. 119). According to the modified form of the gaseo-molten hypothesis, it represents the formations of the volcanic era which followed the formation of the original crust.

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[1] Van Hise, Bull. 86, U. S. Geol. Surv., p. 476.

Earlier Views Concerning the Archean.

In explanation of the Archean system, many different hypotheses have been suggested at one time and another, most of them starting with the Laplacian hypothesis as a beginning. Some of these hypotheses have at least a historic interest. One is that the Archean rocks are completely metamorphosed sediments; a second, that they are igneous rocks produced by the fusion of sediments; and a third, that they are igneous rocks intruded beneath the oldest known sedimentary rocks after the deposition of the latter.

1. The hypothesis that the Archean rocks are metamorphosed sediments was originally based on the assumption that schistosity and gneissic structure were an expression of stratification; that is, that everything which resembles stratification is really such. So long as this view obtained, it was natural that the gneisses and schists should be regarded as of sedimentary origin; but since it is now known that such structures may be developed in sedimentary rocks, independent of stratification, and in igneous rocks as well, the argument loses its force.

If the Archean rocks are primarily metamorphosed sediments, it would seem that there should be somewhat wide-spread evidence of the fact in the structure of the system. So thick a series of sediments would surely have been made up of layers of varying physical and chemical composition. From such a series, no matter how completely metamorphosed, it is not probable that the original distinctions of constitution would have been generally obliterated; but in most of the Archean, no such succession of strata as would be expected if the rocks were dominantly meta-sedimentary exists. This point has special force when it is remembered that it holds not for one region only, but for each of the many regions, some of them of great extent, where the Archean rocks have been studied. It would appear that such effective and wide-spread obliteration of the characteristics of sedimentary rocks could only have been brought about by their fusion; and in this case the product, on solidifying, should no longer be regarded as metamorphic rock, but as igneous rock instead.

A special phase of this hypothesis makes the Archean the altered product of a chemical precipitate from the original ocean. This hypothesis never met with general favor, and has rarely been seriously entertained.[1]

2. A second hypothesis which has been advanced is that the Archean, at least locally, consists of igneous rock produced by the fusion of deeply buried sediments.[2] If this hypothesis were true, the igneous rocks produced by the fusion of sediments should grade up into sedimentary rocks above; they should not be separated from them, as they generally are, by an erosion unconformity. Otherwise it would be necessary to suppose that the lower igneous series was fused long before the upper series was deposited, and that the beds which originally overlay the igneous series, and which were not fused, were subsequently removed by erosion before the deposition of the existing superior, unconformable, sedimentary series. While this sequence of events could not be disproved for certain localities, it is not probable that it represents the general history of most regions where the Archean occurs.

3. A third hypothesis is that the Archean represents igneous rock

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[1] Hunt, The Taconic Question in Geology and the Origin of Crystalline Rocks Trans. Roy. Soc. Canada, Vols. I and II. The untenability of this hypothesis was shown by Irving, 7th Ann. Rept. U. S. Geol. Surv., p. 383.

[2] Lawson, Ann. Rept. Canadian Geol. Surv., 1887.

intruded beneath the sedimentaries after the deposition of the latter, and that they were brought into their present lithological condition by metamorphism subsequent to their irruption. This hypothesis is distinct from the last in that it involves the intrusion of the igneous rock, rather than its formation *in situ,* and in that it does not specify that the source of the lavas was sedimentary rock. It is like the preceding in that it makes the Archean a meta-igneous series.[1] Since the sedimentary rocks overlying the Archean do not, as a rule, show the contact metamorphism which this hypothesis demands, and since the unconformity between the two series is generally an unconformity of erosion, not of irruption, the hypothesis fails to explain the facts. Furthermore, the hypothesis, as a general explanation of the Archean, is an audacious one, for it supposes that igneous intrusions have come in at the base of the known sedimentary series, not in one place only, but generally where the base is accessible, thus commonly concealing the floor on which the oldest sediments were deposited. So violent an assumption makes the hypothesis based upon it improbable.

Though the hypothesis can hardly be accepted as a general explanation of the Archean, it does not follow that the oldest sedimentary rocks nowhere rest, with irruptive unconformity, on igneous rocks.

The Archean in other countries.—The general characters and relations of the Archean complex already given for North America seem to be duplicated in other continents. Corresponding systems of rocks, made up primarily of meta-igneous, but subordinately of inextricably involved meta-sedimentary rocks, are known in all continents. The general characteristics and relations of the Archean, as developed in North America, therefore appear to be essentially world-wide.

In Great Britain, the Lewisian gneiss appears to correspond with the Archean of North America. This formation was derived by mechanical deformation from a complex aggregate of eruptive rocks of different ages, and in one area there appears to be a group of still more ancient sedimentary rocks through which the gneiss was intruded.[2]

In Norway, coarse-banded gneisses (Grundfjeldet, Urberget), with a wider petrographic range than the Lewisian gneiss of Great Britain, are regarded as Archean. The gneisses seem to have originated from acidic and basic eruptive rocks. With the gneiss is associated another group of rocks of meta-sedimentary origin affected by dikes and sills of igneous and meta-igneous rocks.[1]

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[1] For review of this hypothesis, see Van Hise, Bull. 86, U. S. Geol. Surv., p. 480.

[2] Geikie's Text-book of Geology, 4th ed., Vol. II, p. 888.

The Archean rocks of Sweden[2] and Finland,[3] as now interpreted, are similar to those of Norway. They consist of meta-igneous and meta-sedimentary rocks, among which is limestone, together with some igneous rocks not notably metamorphosed.

In France, the Archean is composed chiefly of gneisses and schists of various types, chiefly or wholly meta-igneous.[4]

In Bavaria, the rocks classed as Archean consist of gneiss (Bojan) remarkable for its uniformity, and of schists and gneisses (Hercynian) which include meta-sedimentary beds, among which is graphitic limestone.[5]

In Spain, gneisses and schists which include some limestone beds (Cipollino = limestone with scales of mica, talc, etc.) are commonly classed as Archean.[6]

Similar rocks regarded as Archean occur in India[7] (Bunkelkund gneiss); in northern China,[8] where the Archean has not been clearly differentiated; perhaps in Japan;[9] in Australia,[10] where gneisses, schists, and meta-sedimentary beds classed as Archean lie at the surface, over an area some 20,000 square miles in extent; in Tasmania;[11] and in New Zealand.[12]

Life during the Archeozoic era.—The presence of carbonaceous material, of bedded iron ores that were once carbonates, of cherts, and probably of limestones, implies the presence of life during the era occupied in the formation of the Archean rocks. Since no fossils have been found, nothing is positively known of the character of the life, and little, except by inference, of its abundance.

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[1] Reusch, Die Fossilführenden krystallinischen Schiefer von Bergen, 1883, and Neues Jahrbuch (Beilage-band), 1887.

[2] Torneböhm papers in Geol. Fören, Stockholm; in Handl. Akad. Stockholm, Vol. XXVIII, 1896; and in reports of the Sverig. Geol. Undersökn.

[3] Sederholm, Bull. Com. Geol. Finlande, 1899; also same author's papers in Tschermak's Mittheil., Vol. XXII, 1891; Fenia, Vol. VIII, 1893; Geol. Fören, Stockholm, XIX, 1897.

[4] De Lapparent, Traité de Géologie.

[5] Gümbel, Geognostische Beschreibung des Oberbayerischen Grundgebirges, Gotha, 1868. Cited by Geikie, Vol. II, p. 801.

[6] De Lapparent, Op. cit.

[7] Medlicott and Blanford, Manual of Geology of India.

[8] Von Richthofen, China, Vol. II.

[9] Kôto, Jour. Coll. Sci., Imp. Univ. of Tokyo, Vol. V, 1893, Pt. III.

[10] David, Proc. Linn. Soc. N. S. Wales, Vol. VIII, 1894.

[11] Johnston, Geology of Tasmania, 1888.

[12] Hector, Handbook of New Zealand, 1883; Haast, Geology of Canterbury; and Hutton, Geology of Tago.

Duration of the Archeozoic era.—Of the duration of the Archeozoic era nothing can be said beyond the general statement that it was very great, and this conclusion is independent of any particular conception of the earth's origin. If the planetesimal hypothesis be the true one, there is no readily assignable lower limit to the Archeozoic system, and the duration of the Archeozoic era may exceed that of all subsequent time.

For convenience of future reference, a table of the principal geologic time-divisions is here added:

General Table of Geologic Time Divisions.

Cenozoic	Present.	
	Pleistocene.	
	Pliocene.	
	Miocene.	
	Oligocene.	
	Eocene.	
	Transition (Arapahoe and Denver).	
Mesozoic	Upper Cretaceous.	
	Lower Cretaceous (Comanche or Shastan).	
	Jurassic.	
	Triassic.	
Paleozoic	Permian.	
	Coal Measures, or Pennsylvanian.	
	Subcarboniferous, or Mississippian.	
	Devonian.	
	Silurian.	
	Ordovician.	
	Cambrian.	
	Great Unconformity.	
Proterozoic	Keweenawan.	
	Unconformity.	
	Animikean. (Upper Huronian of some authors.)	
	Unconformity.	
	Huronian. (See p. 161.)	
	Great Unconformity.	
Archeozoic	Archean Complex.	Great Granitoid Series. (Intrusive in the main, Laurentian.)
		Great Schist Series. (Mona, Kitchi, Keewatin, Quinnesec; Lower Huronian of some authors.

The following classification of the pre-Cambrian has recently been proposed by a Committee of the United States and Canadian Geological Surveys appointed to consider the question:

CAMBRIAN—Upper sandstones, etc., of Lake Superior.
Unconformity.
PRE-CAMBRIAN.
Keweenawan (Nipigon).
Unconformity.
Huronian.
- Upper (Animikie).
- *Unconformity.*
- Middle.
- *Unconformity.*
- Lower.

Unconformity.
Keewatin.
Eruptive contact.
Laurentian.

The Lower and Middle Huronian of this table,[1] taken together, correspond to the Huronian of the table above. This classification was published after this chapter was in the hands of the printer, and has therefore not received, in the pages which follow, the consideration to which its history entitles it. It will be noted that its principal departure from the preceding classification lies in the threefold, instead of twofold, division of the rocks between the Archean below, and the Keweenawan above.

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[1] Jour. of Geol., Vol. XIII, p. 104.

CHAPTER IV.

THE PROTEROZOIC ERA.

To the Proterozoic[1] era is assigned the time between the close of the formation of the igneous complex just described, and the beginning of the lowest system which is now known to contain abundant well-preserved fossils; or in other words, the time between the close of the Archean and the beginning of the Paleozoic. During the Proterozoic era several great series of sedimentary formations, unconformable with one another, were formed (p. 160). These sedimentary series were rather freely interlarded with igneous sheets, some of which were intruded as sills, and some spread upon the surface while the clastic beds were being formed. It was therefore a time when igneous activity was still rather pronounced, though by no means so overwhelmingly dominant as in Archean times. Sedimentation had become, for the first time, the leading process in the formation of the geological record.

In contrast with the Archeozoic, the dominant feature of the time, and the feature which was really most significant in the history of the earth, was the effectiveness of the weathering processes and of the hydro-atmospheric work upon the land which furnished the material for sedimentation. These processes were really more significant than the sedimentation, because they were prerequisites to it. They, in turn, were dependent on the deformations of the body of the earth which gave the topographic conditions necessary for erosion, and on atmospheric and thermal conditions. The sedimentary deposits of the era, however, constitute the main part of its record, and are the principal subject of geologic investigation.

The Proterozoic rocks include the first great series of strata which imply mature weathering, and the prolonged and continuous deposition in the sea of weathered material derived from the adjacent lands. It is important to emphasize the inauguration of the reign of these processes, for they have been the dominant ones ever since. It is not to be overlooked, however, that the vulcanism which had predominated in the Archean era was still a factor, though a declining one. Locally it still made larger contributions than sedimentation to the formations of the era, and such has been its habit in all later times. But, taken as a whole, Proterozoic times, as the descriptions of the formations will show, were marked by more igneous activity than the Paleozoic, Mesozoic, or Cenozoic eras that follow, and the Proterozoic may therefore be regarded as a transition-time between the profoundly igneous era that preceded, and the markedly sedimentary eras that followed.

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[1] Proterozoic, as here used, is a synonym for *Algonkian* as used by the U. S. Geol. Surv.

Stratigraphic Relations of the Proterozoic Rocks.

The Proterozoic series are generally separated from the Archean below and from the Paleozoic above by unconformities (Vol. I, p. 18). Unconformities vary greatly in extent and significance. Great unconformities usually involve three elements: First, a change of attitude in the lower formation, as the result of which it is subject to erosion; second, a period of erosion during which its upper part is truncated; and third, another change resulting in the deposition of the upper series on the eroded surface (Figs. 49 and 50). In some cases the unconformity may be due, theoretically, to a withdrawal and return of the sea, or to a lifting and subsidence of the land, or to both acting in coöperation. But if the beds below the unconformity are deformed, it is obvious that more than mere change of level was involved. In most cases the unconformity between the Archean and the Proterozoic systems indicates that the former was notably deformed, and afterwards subjected to prolonged erosion, before the deposition of the latter. It is usually an invasion of the sea which furnishes the conditions for

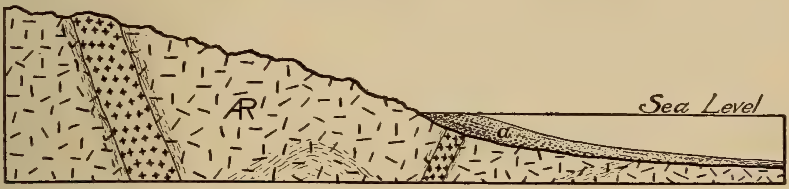

Fig. 49.—Diagram showing Archean land (Æ) with sedimentation, *a*, along its borders. The coarser sediments are being deposited near the shore; the finer, farther from it. (Compare Fig. 50.)

deposition, particularly where the deposits form a wide-spread and thick series; but this is not necessarily the case, for lodgment may take place in interior basins and on low gradation-planes. In such systems as the Proterozoic, where fossils are generally wanting, it cannot be asserted that the sea was involved, though the probabilities favor a marine origin for most of the sediments.

Though the Proterozoic rocks are generally unconformable on the Archean, unconformity between the two systems cannot be asserted to exist at every point where their contact has been seen. It is, however, so general as to show that wide-spread changes of attitude (probably warpings of the crust) took place after the formation of the Archean, and before the formation of the known Proterozoic. Great lapses of time were doubtless involved in these changes, but of the history of the interval recorded by the unconformity there is little more than conjectural knowledge. It is clear, however, that where unconformity exists, the Proterozoic beds above the unconformity are not the oldest sedimentary beds derived from the Archean, for the material removed from the eroded Archean surface was deposited somewhere, and that before the beds immediately above the plane of unconformity were laid down.

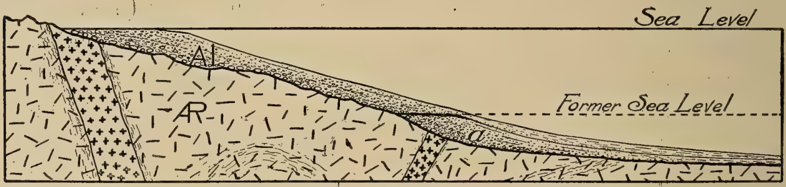

FIG. 50.—Diagram representing the same region as Fig. 49, after subsidence. The *a* of this figure corresponds to *a* of Fig. 49. It is to be noted that fine sediments overlie the coarse sediments deposited at an earlier time in the right-hand part of the figure.

While unconformity between the Archean and the Proterozoic is the rule, so far as their contacts are known, it should be noted that such unconformity is presumably not universal. There were probably places, even on the land-areas, where the surface of the Archean did not suffer notable erosion before the deposition of Proterozoic sediments upon it, and there were quite certainly such places in the areas continuously covered by the sea. Relations of conformity between the two systems may therefore exist over great areas where their contact is not exposed, and perhaps in some places where it is.

A sequence of events which might have given rise to the unconformable relations of the Archean and the Proterozoic, where seen, is illustrated by Figs. 49 and 50. Fig. 49 represents an area of land composed of Archean rock in such a position as to suffer erosion. The sediments derived from it are washed down to the sea and deposited in its waters (*a*). In Fig. 50, the land of the preceding figure is represented as having sunk so as to be partially submerged. A part of the sediments washed down from the remaining land are being deposited on the surface which formerly suffered erosion. These sediments (*Al*, Fig. 50) overlie those deposited at the earlier stage. The latter (*a*) are the older, though the former may be the oldest now accessible.

Subdivisions.

No classification of the formations of the Proterozoic era has been widely accepted as of general application, but where these rocks are best known, at least three great unconformable series or systems are referred to this era. These several divisions are of such thickness and extent that their local names may well be taken for the great subdivisions of the rocks of this era. In the order of age, these systems are (1) the Huronian, (2) the Animikean or Penokean, and (3) the Keweenawan (p. 160). The first system is named for the region north of Lake Huron, where the rocks were first differentiated. The names of the second system come from localities in northeastern Minnesota and northwestern Wisconsin respectively, where the rocks are well developed, while the name of the third system is derived from the Keweenaw peninsula of northern Michigan, on the south shore of Lake Superior.

Each of the systems in this region measures thousands of feet in thickness, but it is important to note that, thick as they are, they do not constitute a complete record of the Proterozoic era. The unconformities between them show that, after the formation of each, there was a disturbance of relations between the sources of the sediments (the lands) and the sites of their deposition (chiefly the sea). Each unconformity appears to mark a prolonged period during which erosion was in progress in the region where the formations are exposed, and deposition somewhere else. The sediments deposited at this time are probably buried under later formations, either within the continent or about its borders, and remain inaccessible. The intervals represented by the unconformities are *unrecorded,* so far as exposed strata are concerned, though they are recorded by the unconformities themselves. It is not impossible that the interval represented by unconformity in one region is represented by known strata in another; but in the absence of fossils, this relation is difficult of determination. Whether the stratigraphic records made in these intervals are ever identified or not, they must be taken into account in the conception of the Proterozoic era as a whole. This era therefore includes the time when at least three thick systems of strata were deposited, and two intervening intervals, represented by unconformities, but not now known to be recorded by accessible strata. Nor is this all; the unconformities between the Proterozoic formations and the Archean, on the one hand, and between the Proterozoic and the Paleozoic, on the other, are to be taken into account. Some portion of the time represented by each of these two great unconformities is to be assigned to the Proterozoic.

Proterozoic Sedimentation.

General considerations.—The stratigraphic relations of the sedimentary Proterozoic formations to the Archean show that they were laid down on the bed of a sea, or other lodgment area, which, at the points where the formations are known, was advancing upon the land. At the time of the advance of the Proterozoic seas (taken as representative of all lodgment areas) upon the lands of Archean rock, the surface of the latter was probably comparable to existing land surfaces of crystalline rock which have been long exposed to weathering, and other phases of erosion. The topography was doubtless more or less uneven, and the surface mantled by soil and residual earths (mantle rock, regolith, geest) which had arisen from the decomposition of the underlying rock (Vol. I, p. 41). Large and small masses of rock, more resistant than their surroundings, probably remained undecomposed, or but partially decomposed, in the earths which represented the products of more complete decay.

The general nature of the clastic sediments laid down on the eroded surface when it was converted into an area of deposition may be readily inferred. They were made up chiefly (1) of the decomposed products already on the surface, (2) of the materials worn from the rocks by the waves, and (3) of river detritus.

(1) One of the first effects of the Proterozoic seas, as they slowly transgressed the land—for it is presumed that this transgression was slow—was to work over, assort and re-deposit the loose material found on the surface. The larger masses of rock suffered relatively little transportation and wear; the sand and small bits of rock were rolled along the bottom and deposited in relatively shallow water, while the finer materials were carried out from the shore and deposited in the more quiet waters beyond (Vol. I, p. 369 et seq.). Deposits of gravel, sand and mud were doubtless being made at the same time at different distances from the shore, and from the gravel on the one hand, to the finest mud on the other, there were all possible gradations (Fig. 50).

Changes in the position of the shore line, and changes in the depth of water incident to the sinking of the land, may have brought about the deposition of fine sediment on beds of coarse material deposited at an earlier time (Fig. 50) when the water where they occur was shallow, and a return of shallow water, as by the rise or aggradation of the sea-bottom, may have caused coarse sediments to succeed the fine in vertical section. In such ways the sedimentary deposits came to be arranged in layers, coarser and finer alternating with one another in vertical section, and grading into one another laterally.

If, at all stages of the sinking which brought land composed of Archean rock below the Proterozoic seas, the waters found coarse and fine materials on the surface they transgressed, and if at all stages the finer parts were carried out from the shores, there should be a widespread deposit of coarse material (gravel) derived from the underlying rock at the base of the sedimentary series (Fig. 50). Such a formation is known as a *basal conglomerate,* and is often one of the best indices of an unconformity. All parts of a bed of basal conglomerate were not necessarily contemporaneous in origin. Thus the coarse material at *a* (Fig. 50) is older than that at *Al,* with which it is laterally continuous.

It is to be especially noted that the loose residual materials which the advancing Proterozoic seas found upon the surface which they transgressed had arisen chiefly by rock decay, and that they were therefore essentially unlike their parent formation in average composition (Vol. I, p. 422).

(2) Besides working over the regolith, the waves doubtless attacked the solid rock wherever exposures were favorable, just as waves here

and there cut into solid rock at the present time. The materials thus derived resembled the parent formation in average composition, and are thus distinguished from those of the preceding class. The sediments of this second class were more or less intimately mingled with those which had been prepared in advance by the decomposition of the rock.

(3) The streams descending from the land brought down their quota of gravel, sand, and mud. The larger part of the river-borne detritus was probably made up of the decomposition products of rock, though a smaller part was probably derived by the mechanical action of running water on undecomposed terranes. Once in the sea, the detritus which the rivers brought down from the land was mingled and deposited with the sediments acquired in other ways. Then, as now, minor quantities of terrigenous sediment were doubtless blown from the land to the sea, and added to that derived from the land in other ways.

Since much of the more soluble constituents of the Archean rock extracted during the processes of decomposition probably remained in solution in the sea-water, it is to be presumed that the clastic sediments were, on the whole, more siliceous than the rock from which they were derived.

The sorting power of moving water takes account of the physical conditions and properties of the materials handled, and not of their chemical constitution; but in the decomposition of Archean rock, the quartz remaining in the residual mantle was generally in larger particles than the aluminous products of the decomposition of the silicates, and under the assorting influence of the waves the quartz grains (sand) were more or less completely separated from the aluminous particles (mud). Thus materials which were unlike chemically were separated from one another because they were unlike physically.

If the Proterozoic seas harbored abundant shell-bearing life, or if their waters anywhere became overcharged with lime carbonate in solution, limestone might have been formed, and should be found associated with the other sedimentary strata.

Extent.—While the beds of sediment accumulated in the Proterozoic are known in limited areas only, it is to be borne in mind that the Proterozoic sediments were in reality as widespread as the Proterozoic seas; for though coarse material from the land is not usually washed out far from the shore, material fine enough to be carried in suspension may be transported great distances, and small amounts of dust are constantly being blown from the land to all parts of the sea. In later geologic time, the life of the sea has occasioned considerable deposits even far from the land, and presumably over the whole of the ocean bottom. The same may have been true from the beginning of the Proterozoic era, for the beginnings of life go even farther back. Both from extra-terrestrial sources, and by precipitation from solution, further additions may have been made to the sediments accumulating on the sea bottom. Sedimentation, even if slow, was therefore doubtless in progress in the deeper parts of the Proterozoic seas as well as near the shores. These general considerations prepare us for the study of the sedimentary rocks now exposed.

The sediments and their interpretation.—The sedimentary beds of the Proterozoic consist of conglomerates (Vol. I, p. 468), sandstones, (Vol. I, p. 422), shales (Vol. I, p. 473), and limestones (Vol. I, p. 378), or of their metamorphic equivalents. Before being cemented or otherwise solidified into firm rock, their materials were gravel, sand, mud, etc. The manner in which such materials are now being derived from previous formations is set forth in Volume I, pp. 110–114, 332–338, and 420–426; the manner in which they are transported by streams, waves, and ocean currents is explained on pp. 115–119, 354, and 364 of the same volume; and the way in which they are assorted, distributed, and deposited is discussed on pp. 177–204 and 355–386. The facts and principles there set forth should be well in mind before the history of this and succeeding periods is studied. In so far as the Proterozoic sediments had the same characters as the modern sediments, it is inferred that they were formed in similar ways.

At the base of the Proterozoic, and at the base of its several systems, there are sometimes found beds of basal conglomerate, which, when traced laterally, are found to abut against steep slopes (cliffs) of the underlying formation. This is exactly the relation which the gravel and shingle of existing beaches sustain to the shore rock. It is therefore inferred that these ancient conglomerates represent ancient shore tracts. As the beds which overlie the basal conglomerates are usually of finer materials, the shore is inferred to have advanced upon the land as sedimentation proceeded, and thus to have given opportunity for the deposition of off-shore material over the coarse shore deposits.

Conglomerate beds which are not basal also occur, and point to changes in the conditions of sedimentation even where unconformities were not developed.

The Proterozoic group also contains great thicknesses of quartzite, which is composed chiefly of grains, and sometimes small pebbles, of quartz, cemented firmly together, usually by the secondary growths of the grains, as explained and illustrated in Volume I (p. 434). It is inferred therefore that in Proterozoic times there was ample opportunity for the separation of quartz grains from the quartz-bearing Archean rocks, and for the rolling and rounding of these grains before they came to rest. As the quartzites of the Proterozoic are sometimes thousands of feet thick, the decomposition which furnished the necessary sand must have been correspondingly great, since in some great formations made of decomposable minerals (such as feldspars, amphiboles, etc.) grains of quartz are absent or rare.

The Proterozoic formations also include great beds of shales, or their metamorphic equivalents, which are interpreted as the clayey products of the same decomposition, and their presence confirms the inference drawn from the sandstones and quartzites. Limestones also are present, from which it is inferred that the waters of the time had become calcareous by processes similar to those now in operation (Vol. I, pp. 429–431, 122, and 107), and that by one or another of the processes by which limestone is now produced, a portion of the calcareous content of the waters was deposited. The limestone affords further confirmation of the preceding inferences, for in the decomposition of crystalline rocks necessary to free the quartz grains and produce clays, the calcareous material is largely dissolved and carried to the sea in solution.

The inference that these ancient sediments were deposited in the same manner as the sediments of modern times is further supported by the ripple and other water-marks on the sandstones and shales, and by the character of their lamination and stratification, which, where still preserved, are precisely analogous to those of the present. By combining evidences of this kind, until by mutual support there is no rational room for doubt, the mode of formation of these ancient deposits is deciphered, and their history read.

The fact that some of the deposits are differently constituted, and tell a different tale, tends rather to increase confidence than to destroy it. Some of the sandstones contain abundant grains of feldspar and other silicate minerals, from which it is inferred that the conditions under which their materials were derived did not permit mature decomposition. As the more notable sandstones (wackes) of this type are associated with lava beds, it is a consistent inference that as a result of the volcanic fragmentation that accompanied the outflows, and the naked surfaces that succeeded them, the ratio of surface wash to decomposition was high, and that fragmental material was borne away to the depositing grounds before being completely decomposed.

To account for the thick series of sediments which exist, it seems necessary to suppose that there was in progress, in some places at least, a slow, quiet warping of the surface which lowered the lodgment basins about as fast as they were filled, and perhaps at the same time raised the areas from which the supply of material came, though this last inference is not a necessary one (Vol. I, pp. 540–541).

By such comparisons and inferences, it is concluded that the general conditions of the Proterozoic times were more like, than unlike, those of the present time, though the points of difference were considerable, especially the greater prevalence of igneous action. Both the resemblances and the differences will be more apparent after the details of the formations are studied.

Geographic Relations of the Exposed Proterozoic to the Exposed Archean.

Proterozoic rocks appear at the surface in many parts of North America, but in few regions have they been clearly separated from the Archean, and in very few have their subdivisions been worked out so as to permit of their separate delineation on maps. Fig. 38 shows the area where rocks of known Proterozoic age lie at the surface, as well as areas where Proterozoic rocks have not been differentiated from the Archean. Where their relations have been made out, the Proterozoic rocks are found to be associated in many places, but not in all, with areas of exposed Archean. Where Proterozoic and Archean rocks are associated at the surface, the former are often found about the borders or along the sides of areas of the latter, or sometimes in narrow belts, or in isolated patches within them. These various relations are shown on the map (Fig. 38), and also by Figs. 51 to 56.

That the Proterozoic formations should be exposed most commonly about the borders of the Archean is made clear by Fig. 51, which shows, in section, the general relations of the Proterozoic systems to the Archean (*Æ*) below, and to younger formations (Ꞓ) above. The

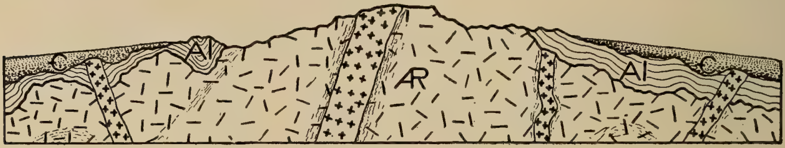

Fig. 51.—Diagram showing a common surface relationship between Archean (*Æ*), Proterozoic (*Al*), and Cambrian (Ꞓ). The Proterozoic (Algonkian) formations appear at the surface between younger and older formations.

same relations are shown in ground-plan in Fig. 52. While the relations shown in these diagrams are common, there are areas of Archean not surrounded or bordered by exposed Proterozoic formations, and areas of the latter not associated with exposed Archean. The former relationship is explained by Fig. 53, where a later formation is represented as lapping completely over the Proterozoic (*Al*). Younger formations

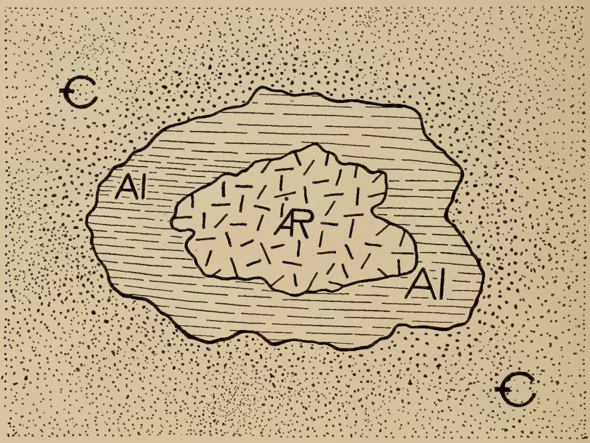

Fig. 52.—Diagrammatic map, showing in ground plan the relations expressed in section in Fig. 51.

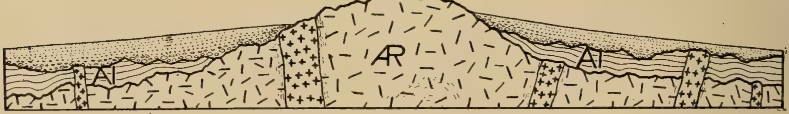

Fig. 53.—Diagram showing how Proterozoic rock (*Al*) may fail to outcrop about Archean (*Æ*).

may completely cover the Proterozoic beds on one side of an area of exposed Archean, while they fail to do so on the other (Figs. 54 and 55).

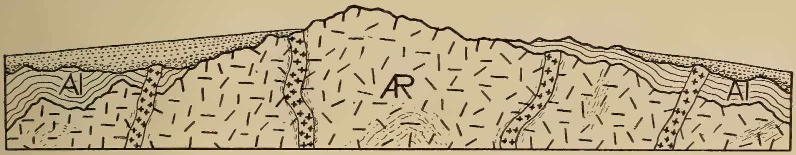

Fig. 54.—Diagram showing how Proterozoic rock (*Al*) may outcrop on one side of an area of Archean (*Æ*) and not on the other.

Belts and patches of Proterozoic rock within areas of Archean (Fig. 56) are often remnants left by erosion, and indicate the former extension of the younger group beyond its present limits.

The occurrence of Proterozoic formations with little surface association with Archean, is illustrated in the southeastern part of South Dakota and the adjacent parts of Minnesota (Sioux quartzite). The Proterozoic rocks in this region may be presumed to lie on an Archean floor, and an adjacent area of Archean, now mostly covered by younger formations, may be supposed to have furnished the sedi-

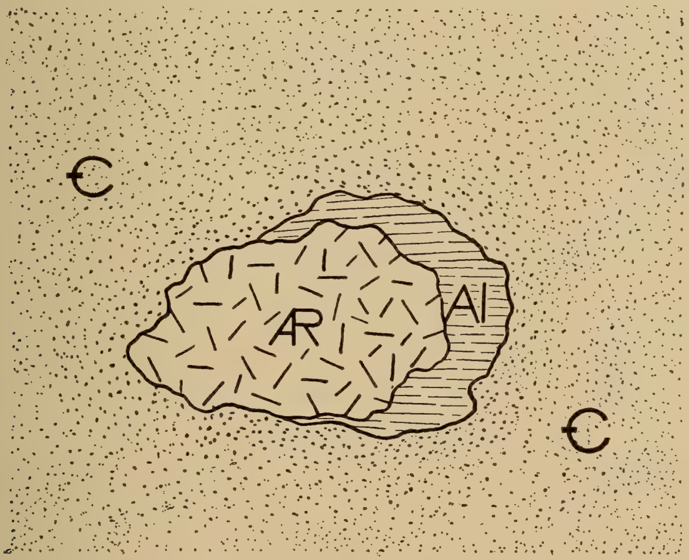

Fig. 55.—Diagram showing in ground plan the relations expressed in section in Fig. 54. *Æ*, Archean; *Al*, Proterozoic; *Є*, Cambrian.

ments for the Proterozoic. A sequence of events which would account for the existing relations is illustrated by Figs. 57 and 58.

It is to be borne in mind that the map (Fig. 38) shows only the exposed areas (so far as known) of the Archean and Proterozoic. The real extent of both systems is much greater. The Proterozoic beds of Wisconsin are probably continuous beneath younger formations with the Proterozoic beds of southwestern Minnesota, and these in turn with those of Missouri and Texas (where the pre-Cambrian rock is probably Proterozoic in part at least) on the south, and with those of the Black Hills and Rocky Mountains (where the undifferentiated pre-Cambrian of the map, Fig. 38, is at least partly Proterozoic) on the west. The total area where Proterozoic rocks exist is therefore

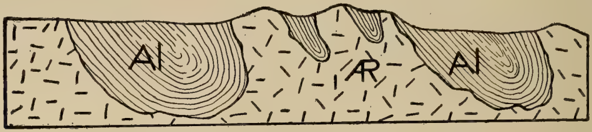

Fig. 56.—Figure showing troughs of Proterozoic rock (*Al*) included in Archean (*Æ*); Marquette region, Mich. Length of section, 2½ miles. (Van Hise, Bayley, and Smyth, Mono. XXVIII, U. S. Geol. Surv.)

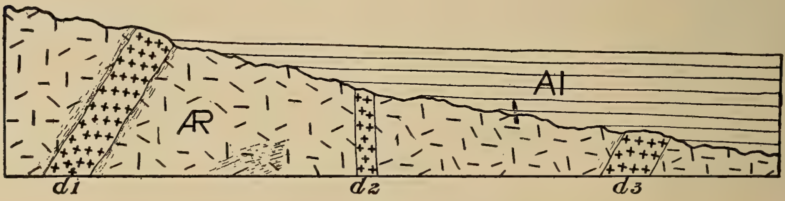

Fig. 57.

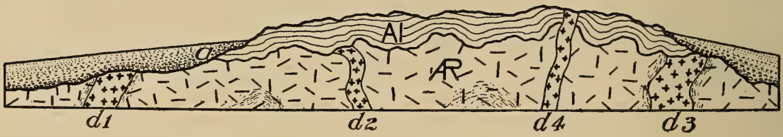

Fig. 58.

Figs. 57 and 58.—Fig. 57 shows Archean rock (*Æ*), on a portion of which Proterozoic sediments (*Al*) have been deposited. Fig. 58 shows the same area after deformation. The Archean rock (*Æ*) not covered by Proterozoic sediments has been depressed and other sediments, *a*, have been deposited upon it. The result is that the Archean rock (*Æ*) is nowhere exposed at the surface, and Proterozoic rock (*Al*) appears at the surface not in association with outcrops of Archean.

believed to be very great, much greater than the area where they are exposed.

The Proterozoic of the Lake Superior Region.

The Proterozoic formations have been most carefully studied and their relations are best understood in the region about Lake Superior, and the formations of this region have been made the basis for the classification of the Proterozoic group as a whole. The Proterozoic rocks of this region are of great thickness, and, as already indicated (p. 165), they are divisible into at least three great unconformable systems, the relations of which to one another, to the Archean below, and to the Cambrian above, are shown diagrammatically in Fig. 59.

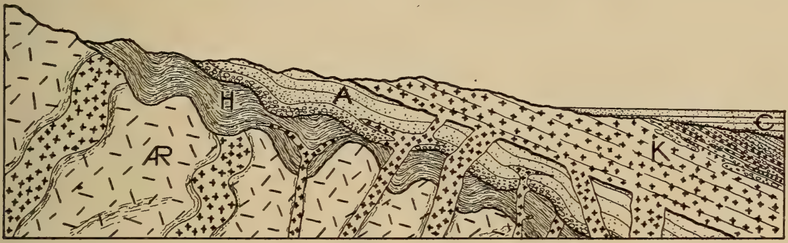

Fig. 59.—Diagram showing the general relations of the three Proterozoic systems of rock in the Lake Superior region. *H*, Huronian; *A*, Animikean; *K*, Keweenawan. The diagram also shows the relation of these Proterozoic systems to the Archean (Æ) below and to the Cambrian (Ꞓ) above. The cross-pattern represents igneous rock. The lines, dots, etc., above the Archean represent sedimentary beds.

During at least some portion of the Proterozoic era there was probably an island of Archean rock in northern Wisconsin. North of Lake Superior there is a much larger area of Archean rock not known to have been submerged during this period. So far as present knowledge goes, these land-areas may have been sometimes united as a result of the elevation, relative or absolute, of the intervening areas. These land-areas were the chief sources of the Proterozoic sediments deposited in the Lake Superior region.

The Huronian system.

(Lower and Middle Huronian of page 161.)

Composition and thickness.—The rocks of this system are chiefly sedimentary. They include all the common sorts of clastic rocks or their metamorphosed products, a subordinate amount of limestone, and beds of iron ore derived by alteration from beds of ferruginous (non-clastic) sediments. The beds of limestone (dolomite) are not known to contain fossils, and their organic origin cannot be affirmed, though this is perhaps their most reasonable explanation.

The period of Huronian sedimentation was long, for in areas favorably situated thicknesses of sediment to be measured by thousands of feet rather than by denominations of a lower order, were deposited. Thicknesses of 6000 feet, and perhaps of 18,000 (see p. 181), are reported. That sedimentation was not uniform throughout the region is indicated both by the fact that the number of formations included in the system is different in different regions, and by the fact that the thickness of a given formation sometimes varies greatly within short distances. In the Menominee region there are five sedimentary formations, in the Marquette region nine, while north of Lake Huron thirteen[1] have been enumerated. The lesser number at some points may be in part the result of erosion which has carried away a portion of the system, but it is also probable that the number of formations did not originally correspond in different parts of the broad area under consideration.

The sedimentary beds of the Huronian system are cut by dikes and affected by igneous intrusions of great and small extent. From the relations of the igneous rocks to the sedimentary, it is clear that extrusions of lava and deposits of volcanic clastics took place at various times during the period, the lavas and tuffs being covered in turn by sediments. Where the metamorphism has been great, it is not now possible in all cases to say whether a given body of igneous rock was intrusive or extrusive, and in many cases where it was intrusive, the date of irruption cannot be fixed. Locally, and even for considerable areas, the igneous rocks are more abundant than the sedimentary in the exposed part of the system (Fig. 60).

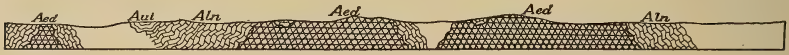

FIG. 60.—Section of the Proterozoic in the Marquette region, N. Mich. *Aln*, Negaunee (iron-bearing) formation (Huronian); *Aui*, Ishpeming formation (Animikean); *Aed*, eruptive diabase or diorite. Length of section, 3 miles. (Van Hise, Bayley, Smyth, Mono. XXVIII, U. S. Geol. Surv.)

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[1] See p. 181, and foot-note 3, p. 151.

Disturbing movements.—After the Huronian formations had attained great thicknesses, the submergence which attended their accumulation was succeeded by a reverse movement, relative or absolute. The beginning of this opposite movement marked the beginning of the end of the Huronian period. The emergence of the land was probably brought about slowly, perhaps as slowly as the submergence which had preceded. Though the border of the sea receded from the position which it had earlier attained, sedimentation continued along its shores at their successive positions. Figs. 61 and 62 will help to make the relations clear. On the supposition that submergence and emergence of the land were gradual, the duration of Huronian sedimentation must have been greater at some points than at others.

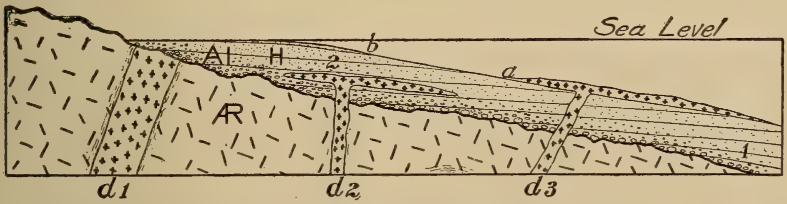

Fig. 61.—Diagrammatic section showing relations which existed around Archean lands during the Huronian period. Huronian sediments (*Al*) are in process of deposition. They are affected by intrusions and extrusions of lava, d_2, d_3, etc.

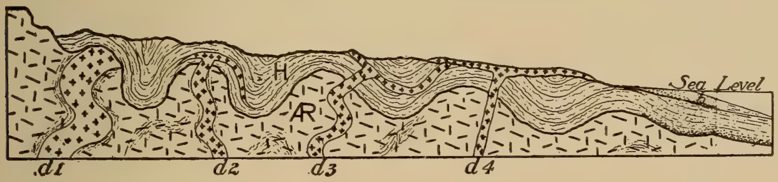

Fig. 62.—Diagram representing the area shown in Fig. 61 after further sedimentation, intrusion, and deformation. Erosion has also affected the deformed beds. It is to be noted that sedimentation is in progress at the right, and that the sediments now depositing, *b*, are conformable on the Huronian sediments, *H*, at the extreme right.

Thus if Huronian sedimentation was brought about by submergence, it began earlier at *a* than at *b* (Fig. 61) and ended later.

Either as the land emerged, or at some time after emergence, the sedimentary beds which had been deposited in horizontal or slightly sloping positions were deformed, being folded in some regions and tilted in others. At the same time it is probable that lava was locally intruded into them and spread out upon their surface. The deformation of the strata and the contemporaneous igneous activity had their effect on the character of the rocks, often rendering them metamorphic. Since the metamorphism is, on the whole, most complete where the deformation of the beds has been greatest, it is inferred that dynamic action was a principal factor in the metamorphism. As a result of the metamorphic change, slates and schistose rocks of various sorts came to be important components of the system. Fig. 63 represents, about natural size, the structure of a piece of Huronian rock after deformation.

It is not to be understood, however, that dynamic and thermal agents were the only ones involved in the changes which the Huronian formations have suffered. The sandstones and the quartzose conglomerates have been transformed into quartzites by other means (p. 170), and the iron-bearing formations, originally laid down as cherty ferruginous carbonates in some cases, and as ferrous-silicate-bearing sediments in others, have been notably changed by percolating waters carrying oxygen, carbonic acid, etc. One of the results of this

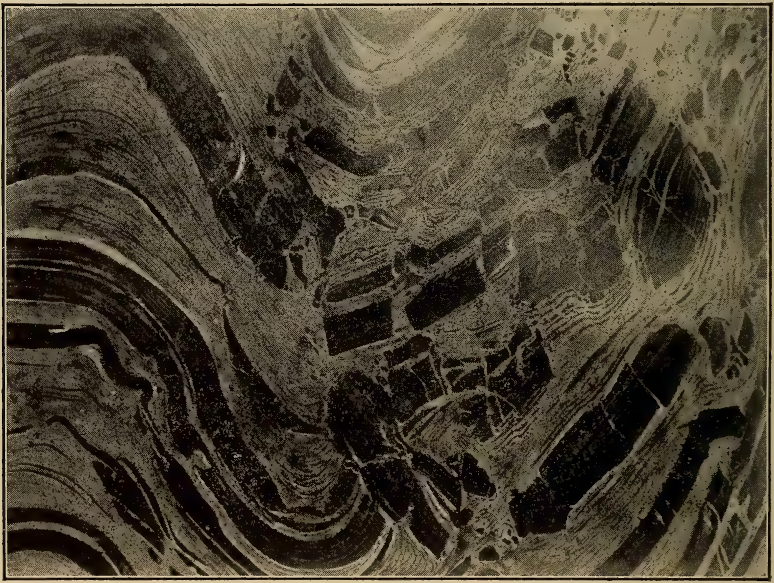

Fig. 63.—Figure showing the deformation of a small piece of Huronian rock. The dark bands are jaspilite. The remainder is iron ore (hematite). The character of the bending and breaking shows that the deformation took place in the zone of combined fracture and flowage. (Van Hise, Bayley, and Smyth, Mono. XXVIII, U. S. Geol. Surv.)

change, brought about by dissolving, recombining, and precipitating, was the production of beds of iron ore, chiefly hematite.[1]

The sections which follow give some idea of the present conditions of the formations.

Sections of the Huronian.—The following Huronian sections, in selected localities where the rocks have been well studied, give some idea of the range of the system.

The Huronian series of *the Marquette region* of northern Michigan [2] rests unconformably on the Archean, and includes, in ascending order, (1) the Mesnard quartzite, with basal conglomerate, and some slate, 110 to 620 feet thick; (2) the Kona dolomite, with some clastic layers, 425 to 1375 feet thick; (3) the Wewe slate, including, besides slate, some conglomerate, quartzite, and schist, 550 to 1050 feet thick; (4) the Ajibik quartzite, which is sometimes schistose, 700 to 900 feet thick; (5) the Siamo slate, with some graywacke and quartzite, 600 to 1200 feet thick; and (6) the highly ferruginous Negaunee formation, which includes sideritic slate, grünerite-magnetite schist, ferruginous chert, jaspilite, and iron ore, and has a thickness of 1000 to 1500 feet.[3] The sideritic slate appears to have been the dominant original type of rock in the Negaunee formation and most of the other phases of this formation have been developed from it. The series also includes some volcanic rocks. The beds are now closely folded and generally much metamorphosed. (Figs. 64 and 65 illustrate the positions of the formations in this region.)

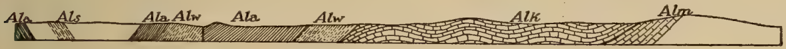

Fig. 64.—Section of Huronian in the Marquette (N. Mich.) region. *Alm*, Mesnard quartzite; *Alk*, Kona dolomite; *Alw*, Wewe slate; *Ala*, Ajibik quartzite; *Als*, Siamo slate. Length of section, 3 miles. (Van Hise, Bayley, and Smyth, U. S. Geol. Surv.)

In *the Menominee* (Michigan and Wisconsin)[4] region, the Huronian system (known also as the Lower Menominee) is unconformable on the Archean, and is divided into three formations: (1) the Sturgeon quartzite, with basal conglomerate, 1000 to 1250 feet thick; (2) the Randville dolomite, including some silicious dolomite, calcareous quartzite, cherty and argillaceous rocks, 1000 to

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[1] For discussion of the iron ores of the Huronian of the Lake Superior region, see Van Hise, 21st Ann. Rept. U. S. Geol. Surv., Pt. III; Irving, Am. Jour. Sci., Vol. XXXII, 1886, p. 255; Van Hise, Vol. XXXVII, 1889, p. 32, and Vol. XLIII, p. 116; and Monographs XIX, XXVIII, XXXVI, and XL, U. S. Geol. Surv.

[2] Van Hise, 15th Ann. Rept. U. S. Geol. Surv., and Van Hise, Bayley, and Smyth, Mono. XXVIII, U. S. Geol. Surv.

[3] According to the classification last suggested (p. 161) the division between the Middle and Lower Huronian is between (3) and (4).

[4] Van Hise and Bayley, Menominee (Mich.) folio, U. S. Geol. Surv.

1500 feet thick; and (3) the Negaunee formation of slight development, corresponding with the formation of the same name in the Marquette region. The series is closely folded, and the beds are often vertical.

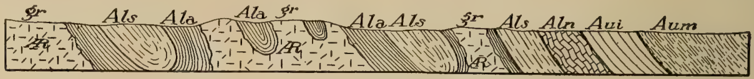

Fig. 65.—Section showing the relations of the Archean, Huronian, and Animikean at one point in the Marquette (N. Mich.) region. *ARgr*, Archean granite; *Ala* (Ajibik quartzite), *Als* (Siamo slate), and *Aln* (Negaunee [iron-bearing] formation) are Huronian formations. *Aui* (Ishpeming formation) and *Aum* (Michigamme slate) are Animikean formations. Length of section, 2 miles. (Van Hise, Bayley, and Smyth, U. S. Geol. Surv.)

In *the Crystal Falls region* of northern Michigan,[1] the Huronian series consists of four formations. In ascending order, these are (1) the Sturgeon quartzite, (2) the Randville dolomite, (3) the Negaunee formation, and (4) the Hemlock formation. The Sturgeon quartzite has a basal conglomerate, and a thickness ranging from 100 to 1000 feet. It grades into the Randville dolomite, which is estimated to have a thickness of 1500 feet. The Negaunee formation is iron-bearing, and is similar to the corresponding formation of the Marquette region. The Hemlock formation consists principally of volcanic rocks, both acidic and basic, and of crystalline schists derived from them. The Huronian rocks of this region have been twice folded, the axes of the folds being nearly at right angles. The rocks are notably metamorphosed.

In *the Penokee-Gogebic region* (Wis.-Mich.)[2] two formations are found, a quartzite (Mesnard) below, and a dolomite (Kona) above. It is unconformable on the Archean, and has a monoclinal structure, the beds dipping at high angles.

In *the Mesabi* (*Minn.*)[3] *district*, the Huronian series consists of metamorphosed graywackes, slates, conglomerates, and granites, unconformable on the Archean. The thickness is at least 5000 feet, and may be 10,000 feet. The bedding and schistose cleavage are nearly vertical.

The Huronian of *the Vermilion* (*Minn.*) *region*[4] is made up of three conformable members, (1) the Ogishkee conglomerate below, (2) the Agawa (iron-bearing) formation in the middle, and (3) the Knife Lake slates above.[5] The Ogishkee conglomerate is a basal conglomerate, unconformable on the Archean. The Agawa formation has a carbonate, slaty facies, and a chert, jasper, iron oxide, and slate facies. Lithologically, it is very like the Soudan formation of the Archean

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[1] Van Hise, 21st Ann. Rept. U. S. Geol. Surv., and Van Hise, Clements, Smyth, and Bayley, Mono. XXXVI, U. S. Geol. Surv.

[2] Van Hise, 10th and 21st (Pt. III) Ann. Repts. U. S. Geol. Surv.; also Irving and Van Hise, Mono. XIX, pp. 127–142, U. S. Geol. Surv.

[3] Leith, Mono. XLIII, U. S. Geol. Surv.

[4] Clements, Mono. XLV, U. S. Geol. Surv.

[5] In the latest publication touching this region, the name of the Agawa formation is omitted. Jour. of Geol., Vol. XIII, p. 94.

(p. 150). The structure of these formations is so complex, as a result of faulting and folding, that thicknesses are not easily estimated. The thickness of the Knife Lake formation has been estimated at 2500 feet, which is probably less than its original thickness.

In *the area north of Lake Huron,* whence the Huronian system derives its name, the strata formerly included in it consist of great thicknesses of rock, divisible into thirteen formations.[1] Though outside the Lake Superior region, the section is here given. In ascending order the formations are as follows:

(1) Gray quartzite, 500 feet; (2) chlorite slate (altered surface volcanic rock), 2000 feet; (3) white quartzite, 1000 feet; (4) lower slate conglomerate (or graywacke and graywacke conglomerate), 1280 feet; (5) limestone, 300 feet; (6) upper slate conglomerate (or graywacke and graywacke conglomerate), 3000 feet; (7) red quartzite, 2300 feet; (8) red jasper conglomerate, 2150 feet; (9) white quartzite, 2970 feet; (10) yellow cherty limestone, 200 feet; (13) white quartzite, 400 feet; total, 18,000 feet. Some of this is now classed as Animikean.

The first five of the above formations, with an aggregate thickness of about 5000 feet, were formerly regarded as "Lower Huronian"[2] and the others as "Upper Huronian." It is now considered possible that all may be Huronian, as that term is here used.[3] The basal member of this series rests on the Archean unconformably, and there appears to be an unconformity between the fifth and sixth members. The uppermost member is overlain unconformably by Cambrian beds.

It is to be borne in mind that the series of rocks here included under the Huronian have but recently been divided into two systems, and that, if future work shall show that the break between them is important and general, rather than local, one of the divisions will doubtless receive an appropriate name and take its place in the series along with Huronian, Animikean, and Keweenawan.

Erosion of the deformed Huronian system.—The deformation of the Huronian formations at the close of the period brought considerable areas of what had been the sites of sedimentation into positions favorable for erosion. The extent of these areas is unknown, and is likely to remain so, since most of the Huronian strata are now covered by later beds which effectively conceal much of the eroded surface of the Huronian, and prevent the determination of its extent. The period of erosion which followed seems to have been long, but its duration cannot be accurately measured. It is certain that great thicknesses of the sedimentary beds were carried away, for the stubs of great folds, truncated before the deposition of the next succeeding system, show that thousands of feet of sedimentary rock must have been removed from their crests. Such remnants of this formation as escaped destruction are in some places known to possess a thickness of about 6000 feet (Marquette district of northern Michigan), and if all the so-called Huronian of the area north of Lake Huron be Huronian, within the meaning of the term as here used, the thickness is 18,060(?) feet.[1] In other places the Huronian strata were completely removed, together with an unknown thickness of the Archean below. According to such data as are at command touching this question, it does not seem improbable that the erosion interval which followed the uplift of the Huronian beds was as protracted as the interval during which they accumulated.

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[1] Logan, Rept. of Progress of the Geol. Surv. of Canada, 1863. Van Hise, 16th Ann. Rept., Pt. I, U. S. Geol. Surv., p. 776.

[2] Van Hise, Bull. 86, U. S. Geol. Surv. See also Jour. of Geol., Vol. XIII, p. 98.

[3] Coleman, American Geologist, Vol. XXIX, 1902, pp. 327–334. Willmott, Am. Geol., Vol. XXVIII, pp. 14–19, thinks most of this Huronian equivalent to the "Upper" Huronian of Canadian geologists.

The erosion of a land surface implies sedimentation about its borders. The materials worn from the Archean and Huronian formations during this period of erosion were probably carried to the sea in the main, and deposited chiefly near its shores; but where the shores were during this time there are no means of knowing, since the deposits then made seem to have been covered, in large measure, by later sediments, and not since exposed.

Contemporaneous events elsewhere.—The processes which were going on about Lake Superior were doubtless in operation about every other land-mass of the time; but it does not necessarily follow that the areas of sedimentation were extended and contracted in other regions just as they were about Lake Superior. It is a principle generally observed in geological nomenclature that the name applied to a series or a formation in one place is not given to a series or a formation in another, unless there is strong reason for believing the two to have been contemporaneous, or essentially contemporaneous, in origin. While, therefore, there are rocks in other localities which doubtless correspond in age with the Huronian of Lake Superior, their contemporaneity has not been proved, and the term Huronian is not generally applied to them.[2]

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[1] Ante, p. 151.

[2] For a fuller description of the "Lower" Huronian of the Lake Superior region, and of the early Algonkian of other regions, see Van Hise, Bull. 86, 16th Ann. Rept. Monos. XIX, XXVIII, XLIII, and XL, and the 21st Ann. Rept., Pt. III, U. S. Geol. Surv. For a discussion of the principles involved in the study of complex systems of non-fossiliferous rocks, such as the Archean and Algonkian of Lake Superior, see, in addition, Irving, 7th Ann. Rept., U. S. Geol. Surv.

The Animikean system.

(The Upper Huronian of some authors.)

General relations.—After erosion had long operated on the deformed Huronian rocks, much of the area about Lake Superior again became the site of deposition. The change was probably brought about by slow subsidence, and as it progressed, the sea appears to have encroached upon the areas which, while land, had suffered extensive erosion. Meanwhile great areas of the earth's surface probably remained continuously under water, and were the sites of deposition. Sedimentation was renewed in the Lake Superior region, probably under conditions similar to those which existed at the beginning of the Huronian period. With the renewal of sedimentation, there was begun a second series of sedimentary beds lying on the eroded surface of the first.

While the Animikean series is, as a rule, unconformable on the Huronian where their contact is seen, it does not follow that this is their universal relationship. Wherever the Huronian formations were not exposed to erosion before the deposition of the next succeeding series, their relation to the Animikean must be one of conformity. The area of conformity, the whole earth considered, must be far greater than the area of unconformity, though the latter is the rule where the contact of the two systems is known. In some parts of the Lake Superior region the subsidence of the Animikean period appears to have been so great that the sea covered the whole of the Huronian series, and reached the Archean beyond. In such places Animikean sediments were deposited on the Archean.

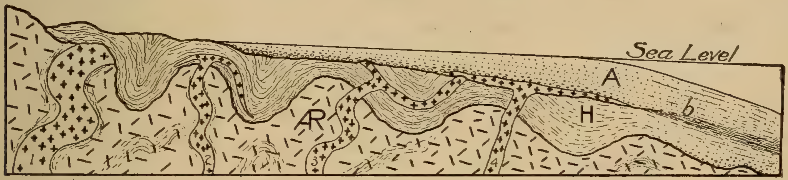

FIG. 66.—Diagram showing same area as Fig. 62, after subsidence, which allows of sedimentation over a part of the eroded surface of *H*. At the right the sediments *b* are conformable on *H*; at the left, sediments *A* are unconformable on *H*.

Composition.—The source of material of the Animikean system is readily understood. All the exposed Archean and all the exposed Huronian formations probably made their contributions. Sediments precipitated from solution also seem to have entered into the system, as in the case of the iron-bearing formations. The character of the beds as first laid down was much the same as that of the Huronian. The fact that the succession of clastic formations is not the same in different parts of the region shows that the conditions of sedimentation varied from point to point about the ancient lands, even within the Lake Superior region.

Certain characteristics of some of the rocks of this system deserve special mention. Within the system there are considerable thicknesses of black shale, the color of which is due to the presence of carbon, often in considerable quantity. Where the rocks are highly metamorphic, the black shale has been changed to graphitic schist. The content of carbon is thought to imply the existence of life, though no fossils have been found in the Lake Superior region.

Another peculiar and important part of the system is the iron ore. Here belong the iron ores of the Mesabi (Minn.), Penokee-Gogebic (Wis. and Mich.), and Menominee (chiefly Mich.) regions. As in the Archean and Huronian, the ore is in the form of ferric oxide (chiefly hematite, Fe_2O_3), but, as in those systems, the ferruginous formations originally consisted of iron-bearing cherty carbonates, and sediments containing ferrous silicate. In so far as the iron was a carbonate, both its original form and the changes through which it has passed seem to imply the existence of life during the period of deposition.

Igneous rocks.—There is reason to believe that igneous forces were active during the period, and that lavas were sometimes intruded into the beds, and into the Archean and Huronian beneatn. The total amount of igneous rock associated with the system is great, frequently predominating (as at the east end of the Penokee-Gogebic range, Mich.) over the rocks of sedimentary origin.

Thickness of sediments and duration of the period.—The period of Animikean sedimentation continued until sediments many thousands of feet in thickness had accumulated. In the Penokee region, that portion of the system which still remains after notable reduction by erosion, has an estimated thickness of about 14,000 feet. In other regions the thickness of what now remains is 5000 to 6000 feet, though the average, where definitely known, is considerably less. It is certain, however, that existing thicknesses often fall far short of the original, for the portions now remaining sometimes (Marquette region) show that they were deformed and metamorphosed when they lay far (probably many thousand feet) below the surface. It is impossible to estimate in years, even approximately, the duration of the period, but it may well have been as great as that of the Huronian.

Deformation and erosion.—After the Animikean formations had attained great thicknesses, the bed on which they rested suffered widespread, but not universal, deformation, and as the sea receded from its former shores it exposed a surface covered by the new formations. So soon as they emerged from the sea, they were subject to erosion (Fig. 67).

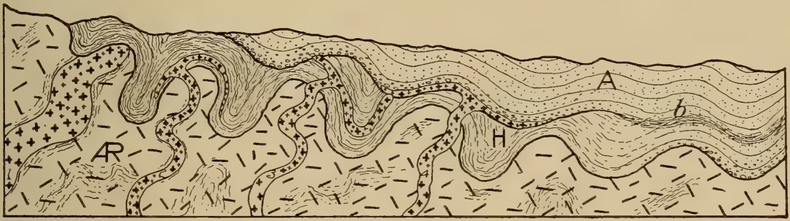

Fig. 67.—Diagram showing same area as Fig. 66 after the Animikean beds, *A*, have been deformed and eroded.

The sediments worn from them were carried down to lower levels and deposited; but the sites of deposition during the early part of this erosion interval have not been seen, or, if seen, have not been recognized. The deformation which inaugurated the period of erosion was probably slow, and the area converted into land seems to have remained above the water for a period of time long enough to allow of extensive erosion. Its amount cannot now be accurately measured, but it is certain that thousands of feet of rock were removed from the surface of the Animikean system in many places.

Alteration of the rocks.—In general the rocks of this system have been less metamorphosed than those of the preceding. This fact, as well as the attitude of the strata, indicates that they have been subject to less dynamic action. In some regions, as on the north shore of Lake Superior, the strata are still approximately horizontal; in others, as on the south shore of Lake Superior, they are notably deformed (Figs. 68 and 69). The forces involved in the transformation of the Animikean beds affected the Huronian systems at the same time, and the metamorphism of the latter may be in part the result of changes effected during the deformation of the former. But while the Aminikean beds are still shales, sandstones, and conglomerates in some places, profound changes during the deformation which followed their depo-

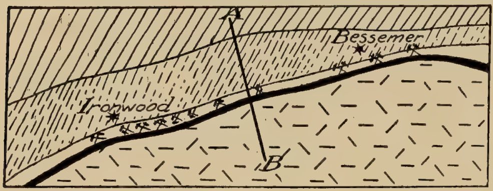

FIG. 68.

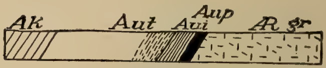

FIG. 69.

FIG. 68.—Map of a small area in the Penokee-Gogebic region of Northern Michigan, a region of important iron mines.

FIG. 69.—Section along the line *Ab* of Fig. 68. Shows the relation of the Animikean beds to the Archean in the Penokee-Gogebic region. *Æ*, Archean granite, *Aup* (Palms formation), *Aui* (Ironwood formation [iron-bearing]), and *Aut* (Tyler slate) are Animikean formations. *Ak*, Keweenawan formation. Length of section, 3½ miles. (Van Hise, 21st Ann. Rept., Pt. III, U. S. Geol. Surv.)

sition, or subsequent to it, have affected them in others, converting these common sorts of sedimentary rock into slates, schists, etc.

Distribution.—The Animikean rocks are most commonly found at the surface either about the borders of the Archean or the Huronian, though isolated areas of them, not in surface association with older formations, are known at a few points (south-central Wisconsin, southwestern Minnesota, and southeastern South Dakota, etc.; Fig. 38). Their exposed parts do not, as a rule, constitute large areas, but their real extent beneath other formations is doubtless great. Their original extent was as great as that of the areas of sedimentation during the Animikean period, and their present extent must be the same, less the area whence they have been removed by erosion.

The following sections of the Animikean in selected localities where the series has been studied in detail, give some idea of its range:

Sections of the Animikean.—In *the Marquette*[1] *region*, the Animikean (Upper Marquette series) is unconformable on the Archean and Huronian, and is divided into three formations: (1) the Ishpeming at the base, (2) the Michigamme, and (3) the Clarksburg. The Ishpeming formation is chiefly quartzite, with a basal conglomerate, but it also includes banded magnetite-grünerite schist. Its thickness is 1550 feet and less. The Michigamme formation was originally composed of ferruginous and non-ferruginous muds and grits, now altered into slates, graywackes, schists, and gneisses. The predominant rocks of the Clarksburg formation were volcanic flows, tuffs, ashes, and breccias, now represented by greenstones. Interbedded with the greenstones are some graywacke, conglomerate, slate, etc. The formation does not lie above the Michigamme formation in stratigraphic sequence. It grades below into the Ishpeming formation at some points, and into the Michigamme at others; while above, it sometimes grades into the latter. In origin, therefore, it was contemporaneous with parts of the Michigamme formation. The aggregate thickness of the Upper Marquette series is not accurately known, but is probably more than 5000 feet, and perhaps as much as 10,000 feet. Figs. 70–72 show the relations of these to older formations.

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[1] Van Hise, 15th Ann. Rept., U. S. Geol. Surv., and Van Hise, Bayley and Smyth, Mono. XXVIII, U. S. Geol. Surv.

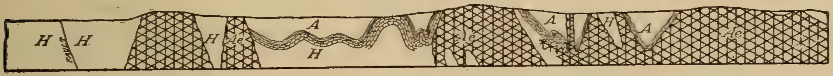

Fig. 70.—Section showing the relations of Huronian and Animikean, in a portion of the Marquette (N Mich.) region, where eruptive rocks exceed the sedimentaries. *H*, Huronian; *A*, Animikean; *Ae*, eruptive diabase. Length of section, 3 miles. (Van Hise, Bayley, Smyth, U. S. Geol. Surv.)

The deformation and metamorphism of the Animikean rocks of this region at the close of this period was great. They now occur in a great east-west synclinorium, and the alterations of the rocks were such as to show that the beds now accessible were in the zone of combined flowage and fracture, and therefore far below the surface, when they were deformed and metamorphosed. In spite of the great changes which these beds have suffered, they are less metamorphic than those of the Huronian system (Lower Marquette) of the same region.

In *the Menominee region*,[1] the *Animikean* (or Upper Menominee) series includes (1) the Vulcan formation and (2) the Hanbury slate. The former, with a ferruginous basal conglomerate, rests unconformably on older rocks, and is made up of quartzites, ferruginous quartzose slates, jaspilites, and iron ores. It has a thickness of 600 to 700 feet. The Hanbury formation is primarily slaty, but includes some iron ore and ferruginous chert, and has a thickness of perhaps 2000 to 3000 feet. The series is closely folded and much metamorphosed. The distinction between it and the Huronian is much less than in the Marquette region. They are separated mainly because of the basal conglomerate at the bottom of the series.

The Animikean system is represented in *the Crystal Falls district* of Michigan [2] by the Michigamme formation, unconformable on the Huronian. Slates, mica schists, ferruginous cherts, actinolite and grünerite schists, and iron ore are included in the formation. The sedimentary beds are affected by dikes, the rocks of which range from acid to ultra-basic. The thickness of the formation is about 2000 feet.

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[1] Van Hise and Bayley, Menominee folio, U. S. Geol. Surv.

[2] Van Hise, 21st Ann. Rept., U. S. Geol. Surv.; and Van Hise, and Clements, Smyth, and Bayley, Mono. XXXVI, U. S. Geol. Surv.

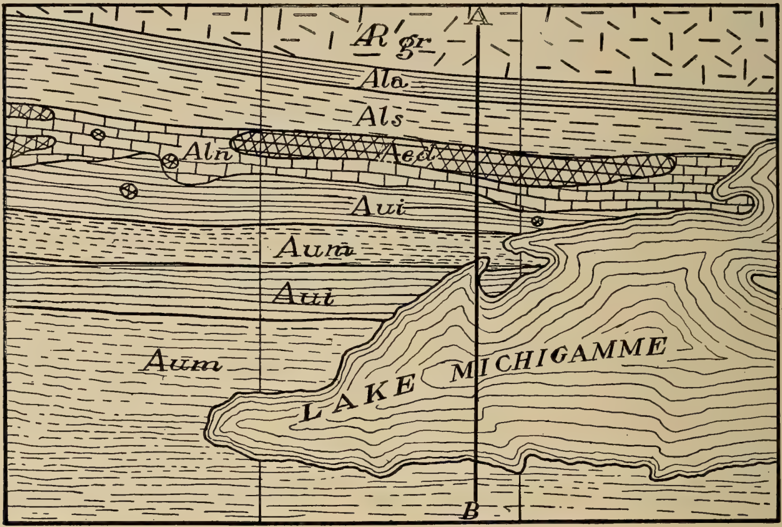

Fig. 71.—Map showing the surface relations of Archean, Huronian, and Animikean formations in a small area in northern Michigan. *Ægr*, Archean granite; *Ala* (Ajibik quartzite), *Als* (Siamo slate), and *Aln* (Negaunee [iron-bearing] formation) are Huronian formations. *Aui* (Ishpeming formation) and *Aum* (Michigamme formation) are Animikean formations. *Aed*, eruptive diabase or diorite. Length of area, 3 miles. (Van Hise, Bayley, and Smyth, U. S. Geol. Surv.)

In *the Penokee-Gogebic region* of Wisconsin and Michigan,[1] the Animikean consists of (1) the Palms formation below, a quartz slate formation, with basal conglomerate, resting unconformably on the Huronian or the Archean, and

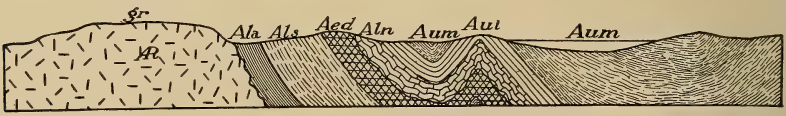

Fig. 72.—Section along the line *Ab* of Fig. 71.

having a thickness of 300–800 feet; (2) the Ironwood formation, consisting of (*a*) cherty iron carbonate, (*b*) ferruginous slates and cherts, and (*c*) actinolitic and magnetitic slates. The cherty iron carbonate represents the original condition of the formation, the others being secondary phases. Iron ore (iron oxide) is found in the lower part of the formation, usually just above the Palms formation. The Ironwood formation has a thickness of about 850 feet. The uppermost formation of the series is (3) the Tyler slate, locally altered to schists The thickness of this formation exceeds 12,000 feet. The structure of the Animikean of this region is monoclinal (dip of 60° to 70°), but a series of transverse folds has been superposed on the monoclinal structure.

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[1] Van Hise, 10th and 21st Ann. Repts., U. S. Geol. Surv.; Irving and Van Hise, Mono. XIX, U. S. Geol. Surv.

In *the Mesabi region,*[1] the Animikean includes three formations. In ascending order these are (1) the Pokegama quartzite, with basal conglomerate, resting unconformably on Archean and Huronian, 0–500 feet thick; (2) the Biwabik (iron-bearing) formation, consisting of cherts, with ferruginous slates, quartzites, and iron ores (iron oxides). The formation from which these varieties of rock were derived consisted largely of granules of green ferrous silicate, to which the name *Greenalite* has been given. The thickness of the Biwabik formation may range from 200 to 2000 feet. Locally it is profoundly metamorphosed by contact with the gabbro and granite of the Keweenawan series. Above the Biwabik

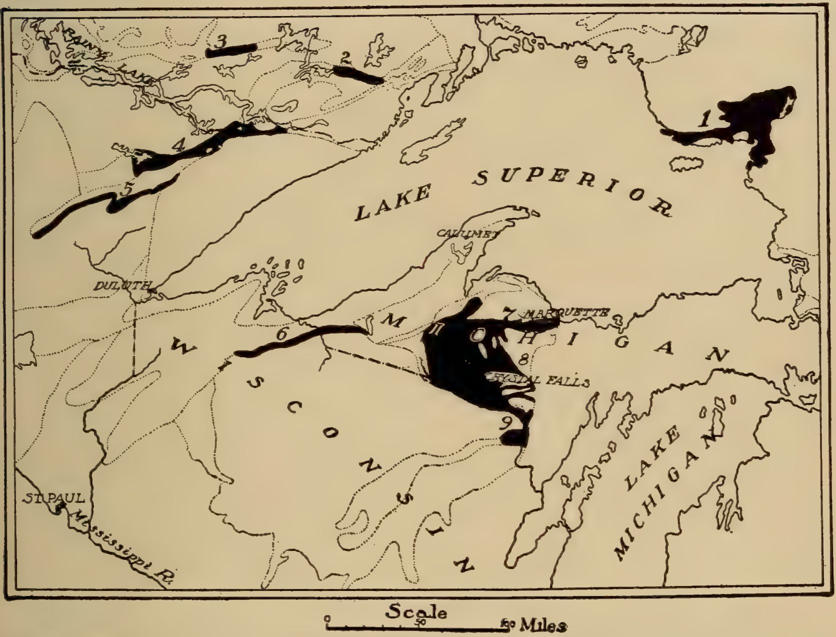

FIG. 72*a*.—Map showing (in black) the position of the iron-producing areas in the Lake Superior region. 1, Michipicoten district; 2, Kamanistquia and Matawin district; 3, Steep Rock Lake and Attikokan district; 4, Vermilion district; 5, Mesabi district; 6, Penokee—Gogebic district; 7, 8, and 9, Marquette, Crystal Falls, and Menominee districts.

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[1] Leith, Mono. XLIII, U. S. Geol. Surv

formation is (3) the Virginia slate, which includes, besides slate, shale, graywacke, and some limestone. Its thickness has not been determined. Like the Biwabik formation, it is locally metamorphosed by igneous contact. All the beds dip south and southeast at angles of 5° to 20°. The dipping beds are gently cross folded, the axes of the folds pitching south. The unconformity of the series with older rocks is shown by (1) basal conglomerate, (2) discordance of dip, (3) differences in amount of deformation and metamorphism, (4) distribution, and (5) relations to intrusive rocks.

In *the Vermilion region*,[1] the *Animikean* series consists of two main conformable members, the Gunflint formation below, and the Rove slate formation above. The former (= the Biwabik of the Mesabi region) is mainly of chert and granular quartzose bands with more or less carbonate, bands of jaspar, magnetic chert, and quartz with crystals of actinolite, grünerite, etc., together with more or less iron carbonate, magnetite, hematite, and limonite (not commercially valuable). The formation has been estimated to be something like 800 feet in thickness. The Rove slate formation (probably = the Virginia formation of the Mesabi region) has, in addition to the slate, some graywacke and some quartzite, and is locally metamorphosed by igneous content. The system also contains some igneous rock. Its thickness is undetermined. The structure of the system is rather simple, being largely monoclinal.

Iron ore in the Lake Superior region.

Production.—The region about Lake Superior yields more iron ore than any other area of equal size in the world. The productiveness of the region has nearly trebled in ten years. In 1902, the aggregate production of ore from that part of this region which lies within the United States was 26,977,404 long tons.[2] This is about 76 per cent. of all that was produced in the United States that year; of this, the Mesabi region produced nearly one-half. In 1900, the last year for which statistics for other countries are available, the iron ore produced in the Lake Superior region of the United States was about 23 per cent. of the total production for that year.

Geologic positions.—The ores of this region are partly in the Archean, as in the Vermilion region of Minnesota, partly in the Huronian, as in the Marquette region of Michigan, but most largely in the Animikean, as in the Menominee and Gogebic regions of Michigan and Wisconsin, in the Mesabi region of Minnesota, and some of those in the Marquette region. The following table gives the production in tons for these several regions for the ten years preceding 1902:

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[1] Clements, Mono. XLV, U. S. Geol. Surv.

[2] Mineral Resources of the United States for 1902.

	1892	1893	1894	1895	1896	1897	1898	1899	1900	1901
Vermilion..........	1,226,220	815,735	1,055,229	1,027,103	1,200,907	1,381,278	1,125,538	1,643,984	1,675,949	1,805,996
Marquette.........	2,848,552	2,064,827	1,935,379	1,982,080	2,418,846	2,673,785	2,987,930	3,634,596	3,945,068	3,597,089
Menominee........	2,402,195	1,563,049	1,255,255	1,794,970	1,763,235	1,767,220	2,275,664	3,281,422	3,680,738	3,679,408
Gogebic...........	3,058,176	1,466,815	1,523,451	2,625,475	2,100,398	2,163,088	2,552,205	2,725,648	3,104,033	3,041,869
Mesabi............	29,245	684,194	1,913,234	2,839,350	3,082,973	4,220,151	4,837,971	6,517,305	8,158,450	9,303,541
Total.........	9,564,388	6,594,620	7,682,548	10,268,978	10,566,359	12,205,522	13,779,308	17,802,955	20,564,238	21,445,903

Reference has already been made on preceding pages (p. 150 and p. 176) to the origin of the ores, and to the literature (p. 179) bearing on the subject. Figs. 73 and 74 illustrate on a large scale the association of iron ore and jaspilite in the Marquette region, and at the same

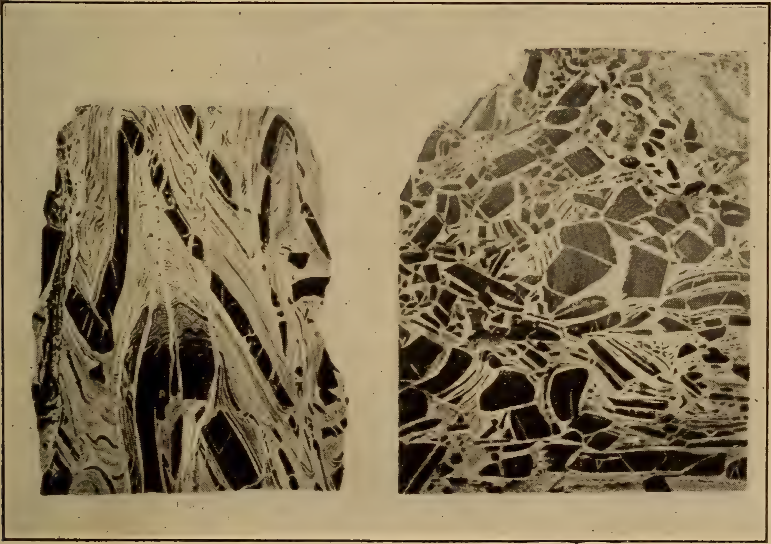

Fig. 73. Fig. 74.

Figs. 73 and 74.—Figures showing deformation and disruption as illustrated by specimens of jaspilite ore from Jasper Bluff, Ishpeming, Mich. (Van Hise, Bayley, and Smyth, Mono. XXVIII, U. S. Geol. Surv.)

time give some idea of the deformation and disruption to which the Huronian rocks have been subject.

The Keweenawan system.

Constitution and thickness.—Overlying the Animikean system unconformably, there is, in some parts of the Lake Superior region, a third series of pre-Cambrian rocks, the Keweenawan.[1] A map of Keweenaw Point (N. Mich.) is shown in Fig. 75, and a section of the Keweenawan system in Fig. 76. The maximum thickness of the system has been estimated at nearly 50,000 feet, but it is not impossible that this estimate is an exaggerated one. If it be correct, the Keweenawan is the thickest body of post-Archean rock referred to any one period. This seemingly incredible thickness may merely mean inclined deposition, with subsequent tilting and shearing, as explained on p. 262, and the estimate be altogether correct.

The lower and thicker portion of the system is made up chiefly of igneous rock, representing a succession of lava flows and intrusions, while the upper part is chiefly sedimentary. The earlier flows of lava seem to have occurred on the land, and to have succeeded one another at short intervals, for the surface of one flow was not sensibly modified by surface agencies before the next overspread it. In places, the scoriaceous surface of a flow is still preserved beneath that next succeeding, and serves to distinguish one lava flow from another. Later in the period, the intervals between the flows of lava appear to have become longer, and thin beds of sediment were deposited between successive sheets of igneous rock. Still higher in the series, the sedimentary beds increase in importance, while the thickness of the intercalated lava beds becomes less, until, in the upper part of the system, the lava beds fail altogether, and there follows a succession of sandstones and conglomerates having an estimated maximum thickness of something like 15,000 feet.

The igneous rocks of the system consist principally of gabbros, diabases, and porphyries, but other varieties are also present, and the range is greater in the upper part of the igneous division than in the lower.

The sedimentary rocks associated with the igneous and lying above

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[1] A general account of this series is given in Vol. I, Geology of Wisconsin, 1881; see also other Wisconsin and Michigan reports, and Mono. V, U. S. Geol. Surv.

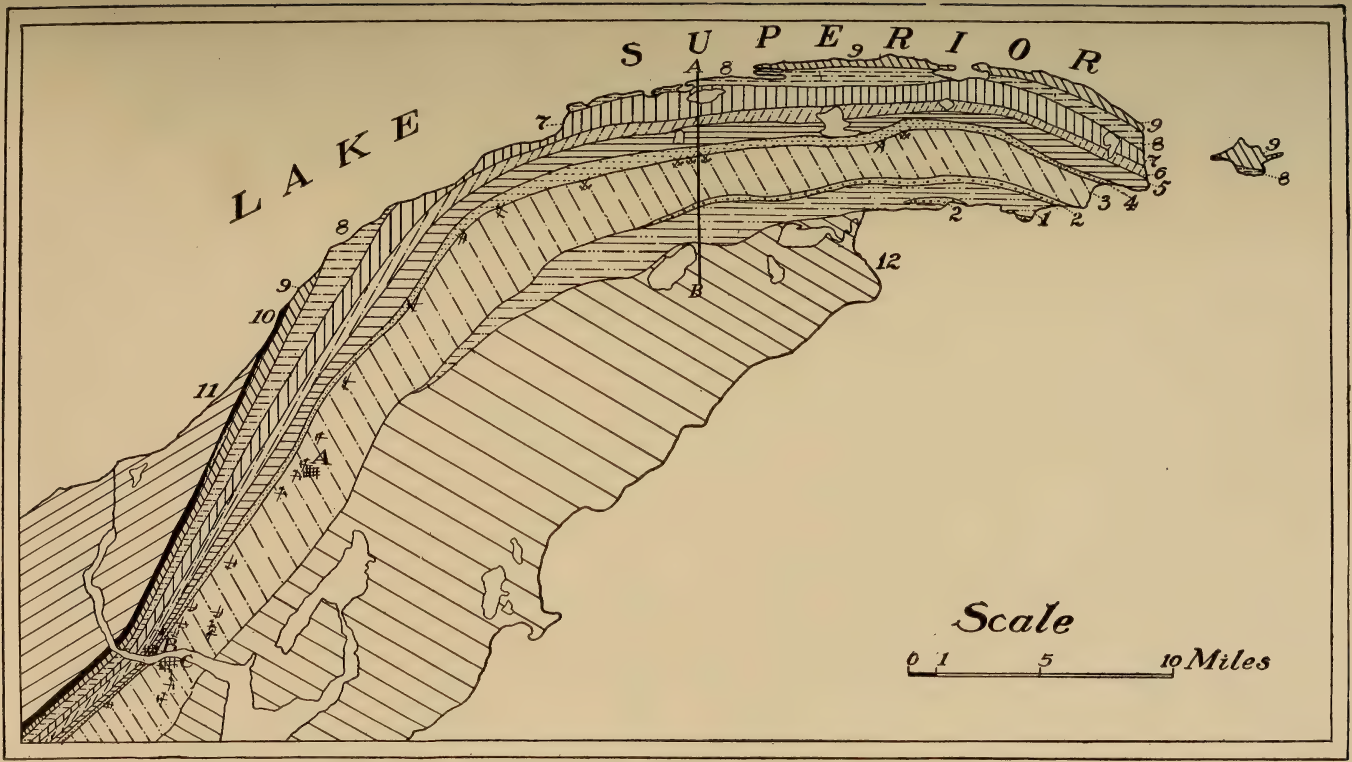

Fig. 75.—Map showing the geology of Keweenaw peninsula (N. Mich.). (1) Diabase and other sorts of igneous rock, including some conglomerate beds; (2) quartz-porphyry and felsite; (3) diabase, melaphyrs, etc., including some conglomerate beds; (4) melaphyrs, gabbros, etc.; (5) diabase, etc., with some conglomerate beds; (6) diabase, etc., with sandstone beds; (7) red sandstone and conglomerate; (8) diabase and some conglomerate; (9) red sandstone and conglomerate; (10) black shale and gray sandstone; (11) red sandstone; (12) Potsdam sandstone. All but the last are Keweenawan. (Irving, Mono. V, U. S. Geol. Surv.)

them were largely derived from the igneous rock itself. Their character is such as to indicate that they accumulated rapidly. In spite of its enormous thickness, therefore, it is not clear that this system of rocks occupied more time in its formation than either of those which had preceded, and perhaps not as much.

In the valley of the St. Croix river, in northwestern Wisconsin and the adjacent parts of Minnesota, there are said to be 65 lava flows and 5 conglomerate beds in succession, with neither top nor bottom exposed.[1] The aggregate thickness of the exposed part of the system in this locality has been estimated at 20,000 feet.

Some of the igneous rocks, such as the gabbros of the Vermilion[2] and Mesabi[3] regions, are intrusive (laccolithic), while others, as in the St. Croix valley, represent fissure eruptions. The laccolithic gabbros and granites of the Mesabi region have occasioned extensive metamorphism in the rocks into which they were intruded. The gabbros (Duluth) of the Vermilion region contain masses of titaniferous magnetite, believed to have arisen from segregation in the original magma. The magnetite is not of commercial value. Dikes and other intrusions of acid igneous rocks affect the more basic portions, and are of common occurrence.

Deformative movements.—The sedimentary part of the Keweenawan series has usually been thought to imply marine submergence, but the sediments may have been accumulated in an interior basin and may be more or less subaërial. If they are marine, their great thickness and their derivation mainly from the lavas of the series itself seem to imply crustal warping throughout the period to renew the erosion fields and furnish the necessary sites for their lodgment. If they are merely lodgment deposits on the low lava slopes of the basin, little movement need be assumed during their deposition, and the subsequent deformation need only have been simple and relatively mild, while the thickness is not incredible (see p. 260). Under either view it was probably during and at the close of this period that the Lake Superior syncline (Fig. 77) was formed, in part at least, and the Keweenawan rocks tilted toward its axis, both from the north and south. It is not to be understood that this syncline has remained

[1] Hall, Bull. Geol. Soc. Am., Vol. XII, pp. 313–340.

[2] Clements, Mono. XLV, U. S. Geol. Surv.

[3] Leith, Mono. XLIII, U. S. Geol. Surv.

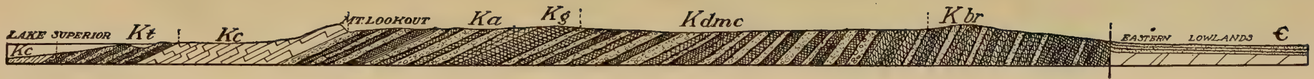

FIG. 76.—Section across the Keweenawan peninsula, along the line *AB* of Fig. 75. *Kbr*, Bohemian Range group; *Kdmc*, diabase, melaphyr, and conglomerate; *Kg*, greenstone group; *Ka*, Ash-bed group; *Kc*, Great conglomerate; *Kt*, Lake Shore trap; *Kc*, Outer conglomerate.

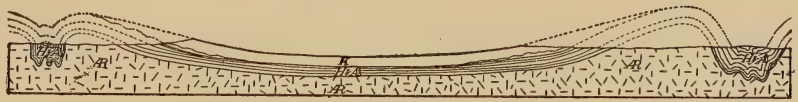

FIG. 77.—Diagram illustrating the development of the Lake Superior syncline. Æ, Archean; *H* and *A*, Huronian and Animikean; *K*, Keweenawan. (Irving, Mono. V, U. S. Geol. Surv.)

a surface depression since this time. On the contrary, it was subsequently filled with sedimentary beds, and the depression occupied by the present lake is the result of subsequent excavation, and is of relatively recent origin. The deep bowing of the series explains, in part, the distribution of the exposed portions of the Keweenawan system, which comes to the surface chiefly about the Lake Superior syncline (Fig. 77). As originally laid down, the system fell far short of covering all of the Animikean, and its distribution, compared with that of the preceding systems, seems to indicate that the land areas of the northern interior were more extensive in the Keweenawan period than during either of the periods preceding.

After the accumulation of the enormous thicknesses of Keweenawan sediments, the region about Lake Superior suffered deformation, apparently in common with other parts of the continent, and this event is regarded as marking the end, or the beginning of the end, of the Proterozoic era in this region.

As a result of the deformation at the close of the Keweenawan, some parts of the area where Keweenawan sediments had been deposited were brought into such an attitude as to be subject to erosion, but this change did not cause great deformation of the strata. They are generally tilted, and locally, folded and faulted as well (Figs. 78 and 79), though this is not the rule. In keeping with their structure, the rocks are not metamorphic. The sandstones, graywackes, and conglomerates are sandstones, graywackes, and conglomerates still. The igneous rock of the series likewise remains, for the most part, in its massive state, not having been made schistose after the fashion of the igneous rocks intruded into the Huronian, and to a lesser extent into the Animikean system.

After the warping which followed the deposition of the Keweenawan formation, the exposed surfaces of Keweenawan, Animikean, Huronian, and Archean rocks suffered protracted erosion. Ultimately the land about Lake Superior again sank, and when the sea came back, a new series of sedimentary beds was deposited unconformably on the eroded surface of those which had preceded. When the sea came back, its waters teemed with life, for the formation then deposited contains abundant fossils. This abundantly fossiliferous formation, resting unconformably on those which had preceded, is classed with the Cambrian system, the oldest system of the Paleozoic

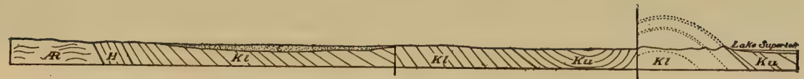

FIG. 78.—Section illustrating the deformation of the Keweenawan beds. Æ, Archean; *H*, Earlier Proterozoic; *Kl*, Lower Keweenawan; *Ku*, Upper Keweenawan; €, Cambrian. Diagram shows faulting and folding. Length of section, 44 miles. (Irving, U. S. Geol. Surv.)

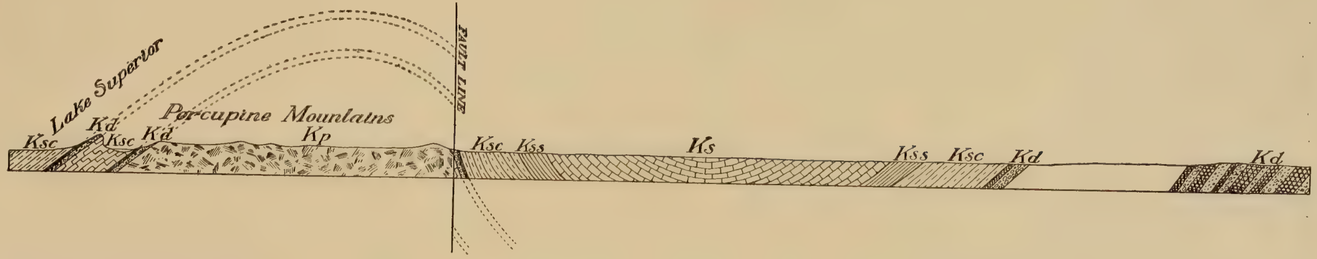

FIG. 79.—Diagram illustrating the deformation of Keweenawan beds in the vicinity of Porcupine Mountain, N. Mich. *Kd*, diabase; *Kp*, porphyry; *Ks*, sandstone; *Ksc*, sandstone, conglomerate; *Kss*, sandstone, shale. Length of section, 15 miles. (Irving, U. S. Geol. Surv.)

era. It is because of the difference in the rocks, faunally considered, below and above the post-Keweenawan-pre-Cambrian unconformity, as much as because of the greatness of the physical changes attending it, that the close of the Keweenawan is taken to mark the end of an era, rather than simply the end of a period.

Copper.—The Keweenawan system contains the most extensive deposits of native copper known. The metal occurs in the pores and cracks of the igneous rock, but more abundantly in the interstices between the pebbles and grains of some parts of the sedimentary beds. In the conglomerate at some of the richer mines, the copper is so abundant as to be one of the important cementing materials of the rock. In its present form, it is believed to be a precipitate from aqueous solution, and to have been concentrated in its present position by ground water. The original source of the metal was probably the igneous rock itself. The date of concentration is undetermined.[1]

In 1875 the Keweenawan formation of northern Michigan yielded 16,089 tons of copper, or about 90 per cent. of all that was produced in the United States. In 1901, the same area yielded 76,165 tons. This was about 26 per cent. of the copper produced in the country that year.[2]

GENERAL CONSIDERATIONS CONCERNING THE LAKE SUPERIOR PROTEROZOIC.

Duration of time.—It is difficult adequately to conceive of the enormous lapse of time involved in the accumulation of such great thicknesses of rock as have been referred to in the preceding pages. If none of the estimates are exaggerated, there is an aggregate of more than 30,000 feet of sedimentary rocks in the Proterozoic systems. The accumulation of such thicknesses of sediment would in itself mean a vast lapse of time, and when it is remembered that the three systems are separated from one another by unconformities, each of which may represent a time interval as long as that involved in the accumulation of a system, and that at least some part of the time during which the unconformities below the Huronian and above the Keweenawan were developed is to be assigned to the Proterozoic, it will be readily seen that the duration of the Proterozoic era was exceedingly great. If length of time may be estimated from thicknesses of sedimentary beds, the duration of the era is comparable to all succeeding time.[1] It is at present impossible to state the length of geological periods in numerical terms, but it would appear that the duration of the Proterozoic era should be spoken of in terms of millions or tens of millions of years, rather than in terms of a lesser denomination.

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[1] For discussions concerning the copper, see Pumpelly, Geol. Surv. of Mich., Vol. I, 1869–73, pp. 19–46; Irving and Van Hise, Mono. V, U. S. Geol. Surv., and Chamberlin, Vol. I, Geology of Wisconsin.

[2] Mineral Statistics for 1902, U. S. Geol. Surv.

The sources of the sediments.—It should also be noted that these extraordinarily thick beds of sediment mean the destruction of a still larger amount of some older rock. The volume of rock destroyed must have exceeded the fragmental product deposited by the amount of mineral matter which remained in solution in the sea at the close of the period, together with such amount as had been carried down by ground water to levels below the surface, and there deposited.

It is important to note further that a large portion of the sediments was produced by *mature decomposition* of older rocks, and this implies that they were not derived by rapid mechanical abrasion such as that which accompanies and follows great elevation and excessive precipitation. The great series of quartzites were derived from the complete decomposition of quartz-bearing rocks, and involved the almost complete separation of the quartz grains from other constituents, while the thick beds of shale arose from the complementary clayey products of decomposition, from which most of the basic oxides had been removed by carbonation. It is scarcely too much to say that the materials of the larger part of these great series first became soils on the surface of the parent areas, and were only removed at a rate that permitted the renewal of the soil beneath as fast as it was washed away above. This mode of derivation is perhaps the most important distinction between the Proterozoic series, as a whole, and the Archean.

The sediments involved in the Huronian formations were derived from the Archean; those involved in the Animikean, from the Archean and Huronian. It follows that the Animikean system had its ultimate origin in the Archean, except in so far as it was derived from igneous rock intruded into the Huronian during or after the formation of that system. If the Archean lands in the vicinity of Lake Superior were high enough at any one time to give origin to the thick sediments

[1] Van Hise, Bull. 86, U. S. Geol. Surv., p. 491.

involved in the Huronian and Animikean systems, their heights would perhaps have surpassed any elevation now existing on the surface of the earth. It is not probable, however, that such enormous elevations existed at any time. It is more probable that as erosion proceeded, the land itself reacted by rising slowly, or that further arching took place, or that the sea bottom sank, drawing off the waters and leaving the land *relatively* higher. In this way, degradation and elevation may have been in progress at the same time, and the one process may never have got far ahead of the other. It is even believed by many geologists that the removal of sediments in large quantities from the land would allow it to rise, and that their deposition on the sea bottom would cause that to sink. This doctrine is known as *isostasy*.

Succession of events.—Reviewing the succession of events in the Lake Superior region, we find (1) that the land was high enough after the Archean rocks came into position for its surface to suffer erosion, and that the period of erosion was long, but that the sites of the earliest sedimentation are unknown. (2) The Archean land then sank or was so eroded or deformed as to permit the deposition of the Lower Huronian (p. 161) sediments on portions of its eroded surface. (3) The area of the former Archean land, together with the Lower Huronian beds about it, was again brought into such an attitude, presumably by crustal warping, that it was subject to a long period of erosion, with contemporaneous sedimentation elsewhere. During the time of the deformation, the rocks involved were metamorphosed. (4) Again the land seems to have sunk, allowing the sea (or at any rate, conditions for deposition) to cover a large part of the territory which had been above sea level, and to deposit upon its eroded surface the sediments of the Middle Huronian system. (5) After this period of sedimentation, the land seems to have emerged, exposing the landward border of the Middle Huronian system, and all the older rocks not covered by it, to erosion. (6) Submergence of the eroded surface of the Middle Huronian was followed by the deposition of the Animikean system. (7) This newly deposited system then emerged over great areas, and was exposed to erosion. This emergence was accompanied by some deformation and metamorphism. At various stages in the progress of these changes there were intrusions and extrusions of lava, on such a scale that the aggregate amount of igneous rock associated with the sedimentary is very great. The igneous activity also aided in the metamorphism of the sedimentary portions of the Huronian and Animikean systems. (8) After erosion of the emerged Animikean system had gone on for a long period of time, flows of lava of unprecedented magnitude were poured out upon the surface of the land over considerable areas and intruded into the existing terranes. (9) Before the outflows ceased, sedimentation began again in the region and soon predominated. Even this long category of physical events is somewhat inadequate, since there are local unconformities at various points, representing minor disturbances of undetermined extent, and many minor changes are probably unrecorded, or their records unrecognized.

It will be seen that oscillations of level were one of the marked characteristics of the Lake Superior region during the Proterozoic era. It will be seen in the sequel that this is a characteristic confined neither to this period nor to this region. All geological history indicates that changes of the relations of sea and land are among the notable events of the earth's history, from the beginning even to the present time. Since many other changes are dependent on them, they are thought to furnish the best basis for the subdivisions of earth history.

It is not now possible to determine, even approximately, either the areal or the vertical extent of the crustal oscillations which took place during the Proterozoic era, but the extent of the area in North America which became land at the close of the Keweenawan—that is, at the close of the Proterozoic—has been estimated with sufficient accuracy to make its cartographic representation instructive (Fig. 90).

Metamorphism.—It has been pointed out that the Huronian rocks are, on the whole, more highly metamorphosed than the Animikean, while the Keweenawan formations are metamorphosed scarcely at all. On the other hand, the Animikean beds are locally as highly metamorphic as the Huronian, indicating intense dynamic action, at least locally, after the deposition of the second great system. Since different sorts of rock behave differently under dynamic action, it follows that some beds are much more highly metamorphic than others associated with them, even though subjected to the same forces. Independent of differences due to variations in the character of the rock, metamorphism has usually been intense about massive intrusions of igneous rock.

There is scarcely a phase of metamorphism which the Proterozoic rocks do not show. The schists, slates, and gneisses are especially the product of dynamic metamorphism; the quartzites are the products of extreme consolidation by cementation; the iron ore is the product of metasomatism, effected by ground waters; while other phases of metamorphism are due to the heat of intruded rock. It is not to be understood that the metamorphism of any considerable body of rock is effected by any one process alone. Dynamic action, which seems on the whole the most important force in metamorphism, always generates heat, and high temperature, especially in the presence of water, facilitates change. So, too, in the case of igneous intrusions, there is often great dynamic action as well as great heat, and water, the agent of chemical change, is always present.

Sequence of events elsewhere.—A consonant but not necessarily identical series of events was probably in progress about every other Archean area in North America, and in the world, during the Proterozoic era; but it does not follow that about every other Archean land area three great systems of rocks were laid down during this long era. About some such areas there may well have been two instead of three systems of Proterozoic rocks, while about others, continuous sedimentation may have been in progress from the beginning of the Huronian period to the end of the Keweenawan. Each Archean land area, especially if distant from others, may have had an independent history, though the great deformative movements were probably general. It is probable therefore that adjacent Archean areas were affected by the same sequence of events, though not necessarily to the same extent. The greater the separation of regions, the less closely are their histories likely to correspond.

Proterozoic Rocks in Other Regions.

Pre-Cambrian sedimentary formations occur in many other parts of North America[1] in relations to the Archean similar to those already described. On the whole, it may be said that they resemble the rocks of the Proterozoic systems about Lake Superior as closely as could be expected under the general principles already enunciated. In many cases they appear in surface association with the Archean, but in some cases no such relation exists.

There are several ways in which the areas of exposed Proterozoic rock, not in surface association with the Archean, may have arisen. (1) If after the deposition of the Proterozoic systems the strata were folded, certain portions might have been brought above sea level, constituting land. If such areas were never buried, the present exposure of the Proterozoic rocks would be explained. (2) Again, during the long period of erosion which succeeded the uplift following the time of Proterozoic sedimentation, the surface may have had its topography greatly changed. If it were brought to the condition of a peneplain with pronounced monadnocks standing upon it, as in south-central Wisconsin, later sedimentation, accomplished during a subsequent period of submergence, may have failed to bury these elevations. Isolated outcrops of Proterozoic might represent such unreduced areas. (3) Or, still again, if the monadnocks were buried, erosion may have since removed the beds which were deposited over them. (4) Uplift and erosion of any surface beneath which the Algonkian rocks lay, would have exposed them without exposing the Archean, if erosion were sufficiently deep to remove all overlying beds, and not so deep as to reach the Archean below.

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[1] For references, see foot-notes, pp. 204 to 215

The following general statements concerning the Proterozoic of different localities give some idea of its extent and relations:

North of Lake Huron.—The Proterozoic formations of this region have already been referred to (p. 181). The Keweenawan series does not seem to be represented, though it appears but a short distance to the west; but its absence violates no principles which have been enunciated. If lava here failed of extrusion, and if the region was not in the attitude necessary for sedimentation during the Keweenawan period, the corresponding system of rocks should be absent. The strata of this area are much less folded and metamorphosed than the corresponding formations in many parts of the Lake Superior region, showing that dynamic action was not equally severe in different regions, and that the degree of metamorphism is not a safe criterion by which to determine age.

The great northern area.—In the extensive area north of the Great Lakes, Proterozoic rocks are known to have wide distribution, and to be associated with still larger areas of Archean. The former often occupy belts (troughs) in the latter (see Fig. 65) and their separation is often a matter of difficulty. At some points about Hudson bay, there appear to be three systems of rocks between the Archean and Cambrian, though it cannot be asserted that these systems correspond with those farther south, and the corresponding names are not commonly applied to them. The several series appear to be separated from one another by unconformities, and the lowest series is believed to be unconformable on the Archean.

The eastern provinces of Canada.—At various points in eastern Ontario, in the province of Quebec, in New Brunswick, Nova Scotia, and Newfoundland, the Proterozoic systems of rocks are represented. In the eastern townships of Canada, there appear to be three series of pre-Cambrian rocks, some of which are certainly Proterozoic. Their relations, however, have not been fully determined. Proterozoic rocks occur in New Brunswick, and in the southern part of this province there appear to be at least two unconformable series of them. In Nova Scotia, the Proterozoic system seems to be represented by about 15,000 feet of sedimentary rocks. In Newfoundland there is a pre-Cambrian sedimentary series about 10,000 feet in thickness which is probably Proterozoic. In most of this eastern region, the work has not been sufficiently detailed to establish definitely the relations of the Proterozoic and the Archean, or even to demonstrate the presence of the latter. In some places the Proterozoic formations are highly metamorphic, and in others they have suffered little change since induration.

The original Laurentian area.—In the area where the name Laurentian was first applied, the area north of the Ottawa and St. Lawrence Rivers between the cities of Montreal and Ottawa, there is a series (the Grenville series) of highly metamorphic rocks, formerly known as the Upper Laurentian. The rocks of the series have been so profoundly metamorphosed that all traces of their original structure are lost, but their composition and general relations leave little doubt that they orginally consisted of sedimentary beds and igneous rocks.[1] Their age is not established, but they are tentatively referred to the early Proterozoic. Nowhere does a series of rocks better illustrate the effect of dynamic metamorphism. Not only were the rocks closely folded and subjected to all the changes which accompany close folding, but along certain planes they were crushed to fragments, and by movements along these planes the resistant fragments were rounded so as to resemble pebbles. Thus arose layers resembling conglomerates. On re-cementation, such rocks are called *autoclastic.* In many cases the pebbles were subsequently flattened by the intense pressure to which they were subjected. The Proterozoic of this district, so far as known, consists of but one series, on which the Cambrian rests unconformably.

In *the Hastings district,* southwest of Ottawa, there is a Proterozoic series similar to that of the original Laurentian area, except that the rocks are less highly metamorphic. They overlie the Archean unconformably.

The rocks of Canada here classed as Proterozoic are known in different regions by different names. To them the terms Cambrian, Huronian, Grenville, and Upper Laurentian have been applied at one time and another in different parts of the Dominion. From this region it has often been reported that they are conformable on the Archean, instead of unconformable; but where detailed work has been carried on by the more refined methods of the present time, an unconformity has generally been found. The unconformity is evident wherever the overlying system is not highly metamorphosed; but where the strata have been much folded and subjected to the changes which profound dynamic action always brings in its train, they have sometimes become so thoroughly crystalline and so complex in structure that they are not easily differentiated from the Archean in the limited exposures which are open to observation. The fact that the Archean was affected by the same dynamic action which metamorphosed the Proterozoic rocks tends to give the two systems uniformity of structure where both have been profoundly altered.

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[1] Adams, Am. Jour. Sci., Vol. L, 1895, pp. 58–69; and Vol. III, 1897, pp. 173–180; also Trans. Roy. Soc. Canada, 1899 and 1901.

The Adirondack region.[1]—Rocks believed to be of Proterozoic age make up the larger part of the Adirondack mountain mass. These rocks belong to two groups: (1) The central mass of the mountains, made up of a complex of igneous rocks which were intruded into (2) a series of pre-Cambrian meta-sedimentary rocks. The igneous rocks sometimes contain bodies of clastic rock. The igneous rocks are of various types (granite, syenite, anorthosite), and are massive in some places and much foliated in others. The clastic series into which the igneous rocks were intruded surround and lap up about the base of the igneous mass. They include crystalline limestone, and quartzose, sillimanitic and graphitic gneisses, together with some gneisses believed to be meta-igneous. The limestone (marble) associated with the gneisses is often massive, a structure which suggests either that it was completely crystallized under static conditions subsequent to the dynamic action which effected the metamorphism of the other sorts of sedimentary rock,[2] or that it behaved very differently from the other sorts of rock when metamorphism was in progress. The metamorphism of the clastic series was probably largely effected at the time of the intrusion of the igneous rocks. The meta-sedimentary rocks are thought to be the equivalent of the Grenville series of Ontario. The floor on which these sedimentary rocks were laid down has not been discovered.

Isolated areas in the Mississippi basin.—Proterozoic rocks come to the surface in isolated areas at several points in the basin of the Mississippi east of the Rocky mountains (Fig. 38). There are some small areas of Animikean (?) quartzite in south-central Wisconsin (the Baraboo quartzite),[3] and in the southeastern corner of South Dakota [4] and adjacent parts of Minnesota and Iowa (the Sioux quartzite) (Fig. 80). In the former place the quartzite has no association with

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[1] Cushing, 54th Ann. Rept. N. Y. State Museum, Vol. I, pp. 258–282; and Kemp, 13th Ann. Rept. N. Y. State Geologist, 1893, pp. 444, 445.

[2] Van Hise, Principles of Pre-Cambrian Geology, 16th Ann. Rept., U. S. Geol. Surv., p. 771.

[3] Irving, Geol. of Wis., Vol. II, pp. 504–519. This may be the Middle Huronian of p. 161. Weidman, Bull. XIII, Wis. Geol. Surv. 1904.

[4] Todd and Hall, Alexandria (S. D.) folio, U. S. Geol. Surv.

Archean, so far as surface exposures show, and in the latter but little. In both localities there is igneous rock associated with the sedimentary. Locally the quartzite has been metamorphosed by dynamic action into quartz schist[1] (Fig. 81). In these places, and especially in Wisconsin, the superior hardness of the quartzite, as compared with the surrounding Cambrian sandstone, has led to the development of striking topographic features. Post-Cambrian erosion, by removing the later formations, has again exposed the pre-Cambrian monadnocks of Baraboo quartzite, much as they were before being buried beneath the later sediments.

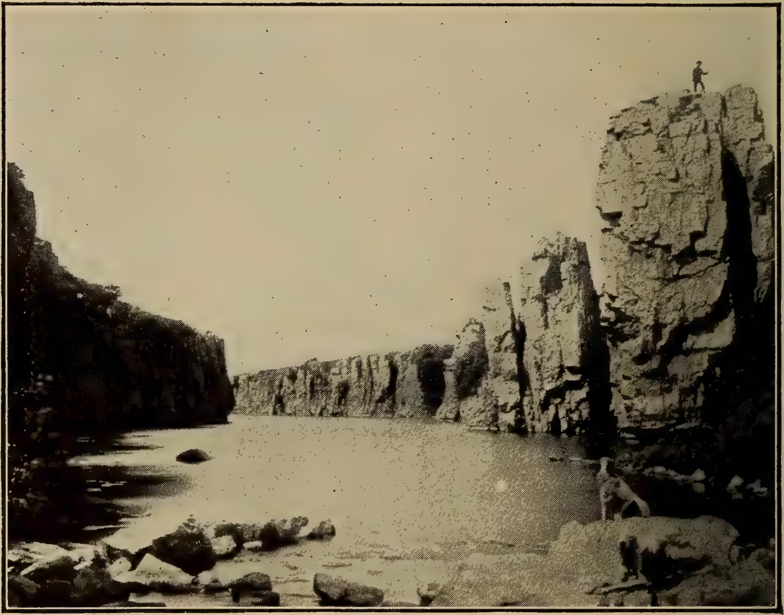

FIG. 80.—The Palisades, Minnehaha County, S. D. Sioux quartzite. (Photo. by Bain Ia. Geol. Surv.)

Rocks of probable Proterozoic age are also known in the Black Hills of South Dakota,[2] making the core of the mountains, and occupying an area about 60 miles long by 20 broad. They consist of closely folded meta-sedimentary rocks, such as mica slates, quartzites, schist-conglomerates, ferruginous chert, mica schists and gneisses, and intrusive masses of granite and basic rocks. From the granite batholiths, the largest of which is eight or ten miles long and nearly as broad, numerous dikes penetrate the clastic beds. The latter afford good illus-

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[1] Van Hise, Jour. of Geol., Vol. I, pp. 347–355.

[2] In addition to general references, see Jaggar, 21st Ann. Rept., Pt. III, U. S. Geol. Surv.

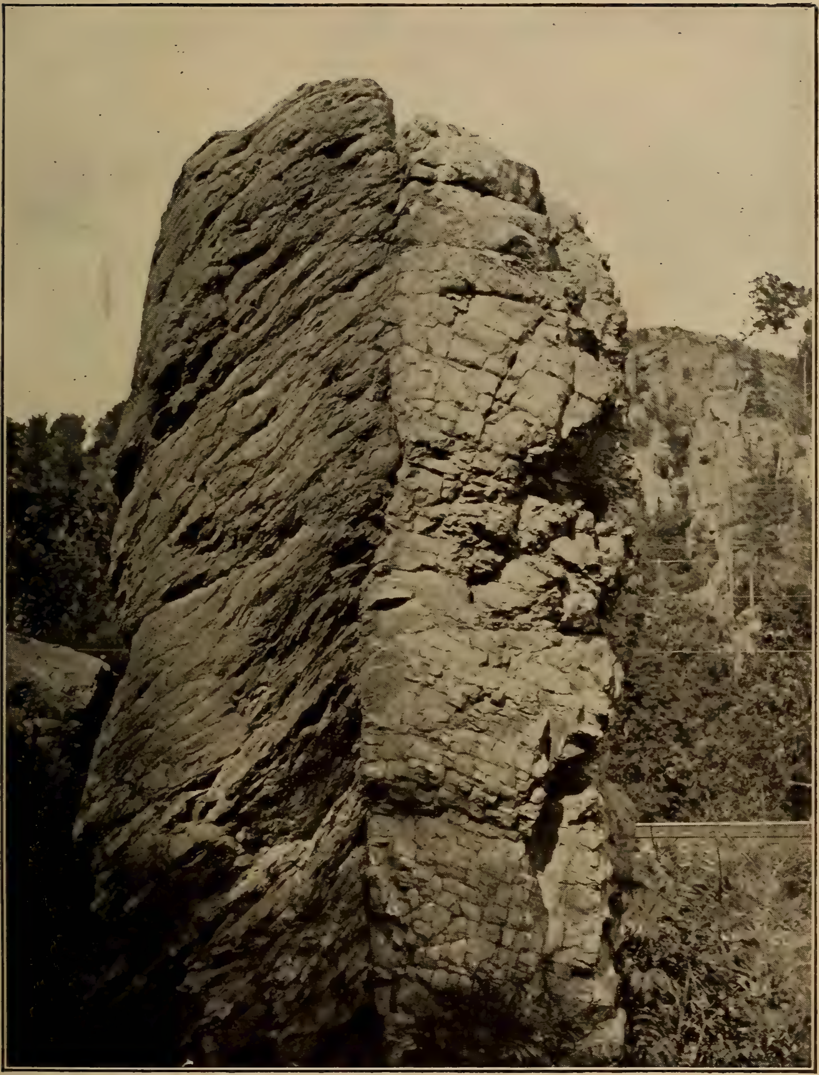

Fig. 81.—Fracture cleavage developed by pressure shown in the left half of the figure, while it is wanting in the right half. The vertical line is a bedding plane. The layer to the left was of sufficiently different composition, or subject to sufficiently different movement, to develop fissility, while that to the right was broken (brecciated) instead. The rock at the left would be called quartz schist, while that at the right is quartzite. Animikean formation near Ableman, Wis. (Atwood.)

trations of the metamorphosing effects of igneous intrusions. The metamorphism is not contact metamorphism in the ordinary sense, but seems rather to combine cementation, injection, metasomatism, and mashing.[1] The date of the intrusions is not known. Figs. 82 and 83 are sections of laccolithic hills in the Black Hills region. They illustrate in a small way the structure of the Black Hills. Fig. 83 is a map of the area of which Fig. 82 is a section.

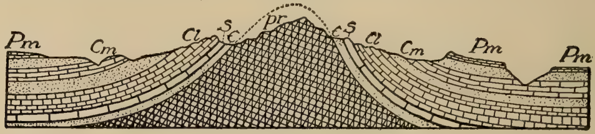

Fig. 82.—A section through Crow peak in the Black Hills region, showing the Black Hills type of structure. *pr*, igneous rock (porphyry); *Ꞓ*, Cambrian; *S*, Silurian (Ordovician); *Cl* and *Cm*, Carboniferous formations; *Pm*, Permian. Length of section, 1½ miles. (Jaggar, U. S. Geol. Surv.)

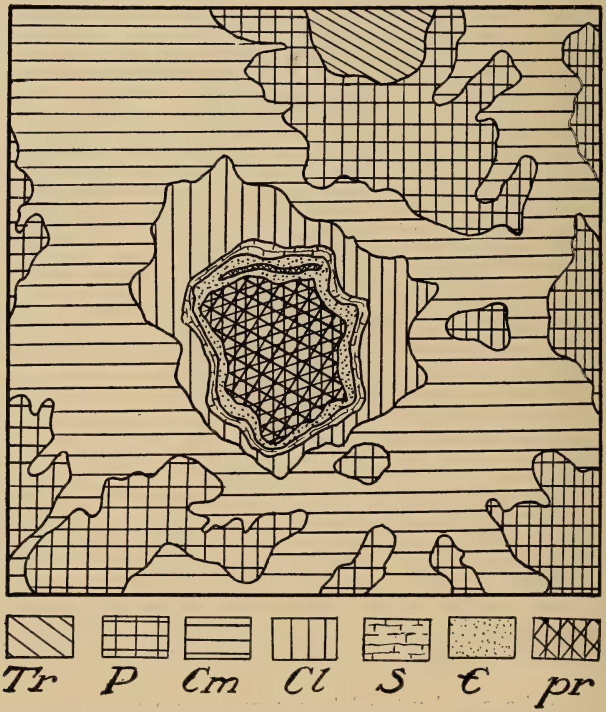

Fig. 83.—Map of the region shown in section in Fig. 82. *pr*, porphyry; *Ꞓ*, Cambrian; *S*, Silurian (Ordovician); *Cl* and *Cm*, Carboniferous formations; *P*, Permian; *Tr*, Triassic. (Jaggar, U. S. Geol. Surv.)

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[1] Van Hise, 16th Ann. Rept. U. S. Geol. Surv., Pt. I, p 814.

Though Archean rocks have not been identified in association with the Proterozoic system of this region, it does not follow that the latter were not derived from the former, so far as they are sedimentary. The lands which gave rise to the sediments appear to have sunk and been buried at some later time, and not again exposed by erosion. The Proterozoic rocks of this region were long buried by formations of lesser age. The uplift permitting the erosion which discovered the older rocks is a relatively recent event (see Tertiary pericds).

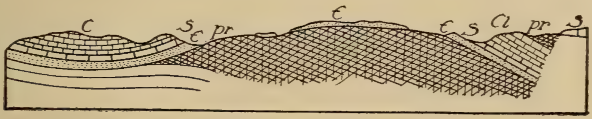

FIG. 84.—Section through Kirk Hill in the Black Hills region, illustrating the type of structure shown in Fig. 82. Legend same as in Fig. 82. Length of section, 3 miles. (Jaggar, U. S. Geol. Surv.)

The Proterozoic system is represented in at least one locality in eastern Wyoming.[1] The rocks are quartzites, schists, silicious limestone, and gneiss, and are locally (near Guernsey) iron-bearing. They have also yielded some copper.

In southeastern Missouri (St. Francis mountains) there are several small areas of pre-Cambrian rock, both sedimentary and igneous. They are not associated at the surface with recognized Archean rock, and their relation to the Proterozoic rocks of other regions has not been determined. As in the Black Hills, the Proterozoic formations of this region were probably buried by younger formations, and their exposure at the surface is the result of erosion following subsequent uplift. The uplift in this area was probably much earlier than that in the Black Hills.

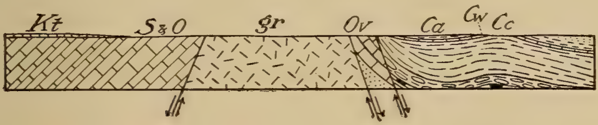

FIG. 85.—Section showing the relations of the Tishomingo (I. T.) granite. *Gr*, pre-Ordovician; *Ov* Ordovician (Viola limestone); *S* and *O*, Silurian and Ordovician (Sylvan shale); *Cc*, (Caney shale); *Cw*, (Wapanucka limestone); and *Ca*, (Atoka formation) Carboniferous; *Kt*, Lower Cretaceous (Trinity formation), Length of section, 5 miles. (Taff, Atoka, I. T. folio, U. S. Geol. Surv.)

In Texas there is at least one series (Llano) of Proterozoic sedimentary rocks, partly metamorphic, associated with igneous rocks which may be Archean. An extensive area of granite (Tishomingo granite) in Indian Territory[2] is also believed to be of pre-Cambrian age (Fig. 85).

The Cordilleran region.—In this region the axial cores of many of the older mountain ranges are believed to be of Archean rock. In many of them there are thick series of sedimentary or meta-sedimentary rocks overlying the Archean, and overlain by Cambrian or younger strata. Where the post-Archean formations are not overlain by Lower Cambrian strata, their Proterozoic age is sometimes open to question. In some places they are highly metamorphic, and in others but slightly so.

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[1] W. S. T. Smith, Hartville, Wyo., folio, U. S. Geol. Surv.

[2] Taff, Tishomingo (I. T.) folio, U. S. Geol. Surv.

Rocks referable to the Proterozoic systems are found in the Medicine Bow range and in some of other mountains of Wyoming; in the Bridger and Little Belt mountains[1] (Belt series, fossiliferous[2]) in Montana, in the Lewiston and Livingston ranges, near the National Boundary, where they are fossiliferous, and some 10,000 feet thick[3] (Fig. 46), and at a few other points in the same State;[4] in British Columbia; in the Wasatch and certain lesser mountain ranges of Utah; in several of the ranges of Nevada[5] (Shell Creek, Egan, Pogonip, and Pinyon); in the Front, Sawatch, Uncompahgre, and Quartzite ranges of Colorado,[6] and in the Grand Canyon of the Colorado in Arizona.[7] In most if not all of these localities the sedimentary beds predominate, but are accompanied by igneous rocks which are in part contemporaneous in origin. The thickness of the Proterozoic rocks in these various localities is often great, but generally unmeasured.

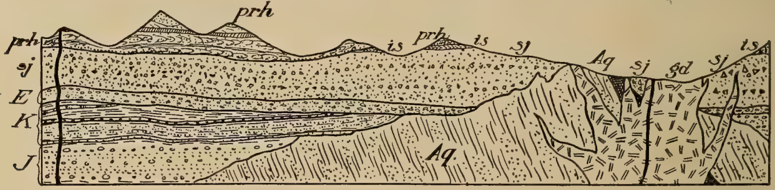

FIG. 86.—Section showing the relations of the Proterozoic formations in the Telluride region of Colorado. *Aq*, Proterozoic quartzite; *J*, Triassic and Jurassic; *K*, Cretaceous; *E*, Eocene; *sj*, San Juan series (tuff, breccia, etc.); *prh*, Potosi rhyolite; *gd*, gabbro diorite. Length of section, 5 miles. (U. S. Geol. Surv.)

In the Canyon of the Colorado (Arizona) the succession of pre-Cambrian formations is easily studied, because of the extensive exposures. The Grand Canyon group[8] (Proterozoic), more than 10,000 feet in thickness, rests unconformably on the Archean, and is in turn covered unconformably by the Cambrian. This great group is itself divisible into two systems by a slight unconformity.[1] The general relations are shown in Fig. 88. Here, as in Montana, a few fossils have been found.[2]

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[1] See Little Belt, Livingston, and Three Forks folios, U. S. Geol. Surv.

[2] Walcott, Bull. Geol. Soc. Am., Vol. 10, pp. 227–44.

[3] Willis, Bull. Geol. Soc. Am., Vol. 13, pp. 316–24.

[4] Weed, 22d Ann. Rept. U. S. Geol. Surv., Pt. II, p. 434. See also the Little Belt, Livingston, and Three Forks (Mont.) folios, U. S. Geol. Surv.

[5] King, Geol. Expl. of the 40th Parallel, Vol. I.

[6] Proterozoic (Algonkian) formations are shown on the Pike's Peak and Telluride folios (U. S. Geol. Surv.) of this State.

[7] See references in Bull. 86, U. S. Geol. Surv.

[8] Powell, Geology of the Uinta Mountains.

In many of these localities the Proterozoic strata are associated with Archean, but the details of their structure and relationships have not been worked out in many places. Enough, however, is known to render it probable that many of these localities, as British Columbia, southwestern Montana, the Wasatch mountains, etc., were within the limits of one geological province in the Proterozoic era. One of the features common to much of this province is the conformity of the Proterozoic strata beneath the Lower Cambrian. Within the province, a succession of formations and events as definite as those of the Lake Superior province will probably be established when the several areas have been studied with equal care; but the order established for this province may not be very similar to that of others, since the sequence of events in different provinces is not necessarily the same.

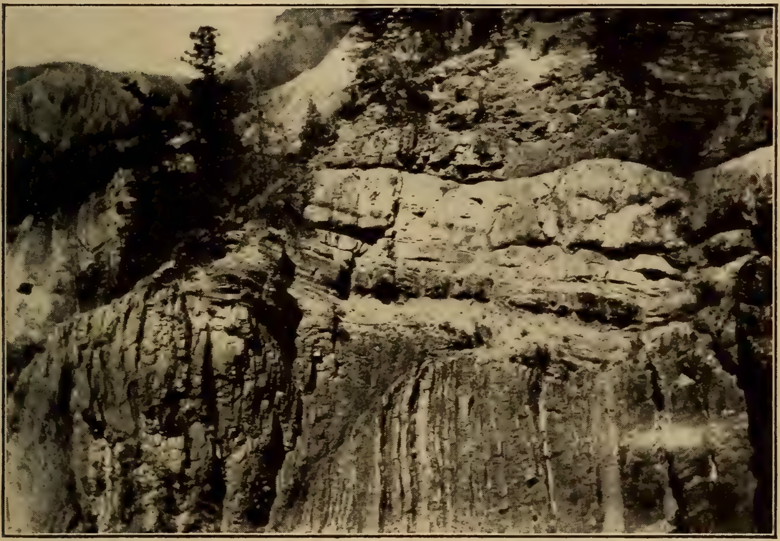

FIG. 86a.—Horizontally-bedded limestone, resting unconformably on vertical beds of Proterozoic Quartzite. Box Canyon, near Ouray, Colo. (R. T. Chamberlin.)

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[1] Walcott, 14th Ann. Rept. U. S. Geol. Surv. and Bull. 30, U. S. Geol. Surv. Walcott gives a three-fold division of the Algonkian.

[2] Walcott, Bull. Geol. Soc. Am., Vol. X.

In the eastern part of the United States.[1]—In the eastern part of the United States there are large areas of metamorphic rock which were formerly classed as Archean. As shown in Fig. 38, these rocks occupy a large part of New England, the southeast corner of New York, and parts of northern New Jersey, the South Mountain district in Pennsylvania, and farther south, the wide belt of the Piedmont plateau lying east of the Appalachian mountains from Pennsylvania on the north to Alabama on the south. This belt of metamorphic rocks contains formations that were sedimentary, and those that were

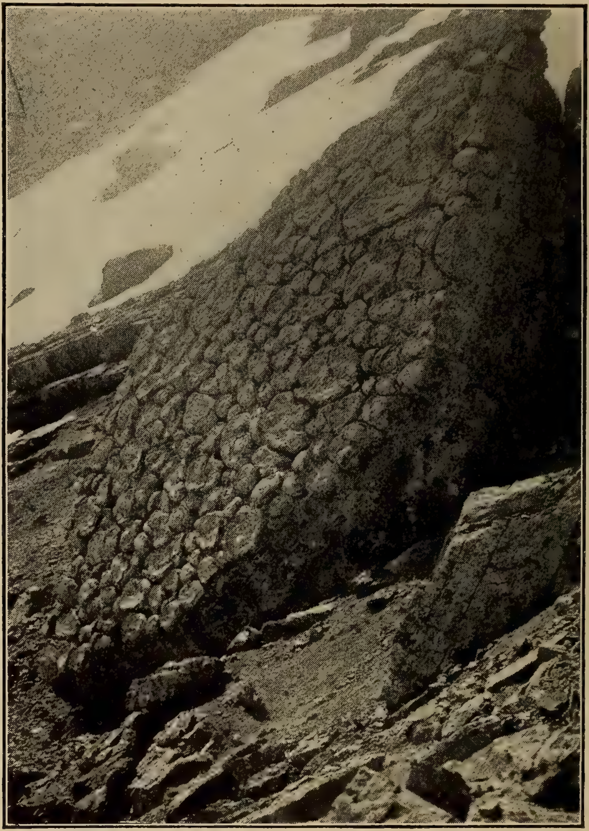

Fig. 87.—Figure showing peculiar polygonal structure in Proterozoic limestone in northern Montana. (Willis, U. S. Geol. Surv.)

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[1] See Bull. 86, U. S. Geol. Surv., and folios, U. S Geol. Surv.

igneous. In some places they are so far metamorphosed as to have lost all trace of their original texture, while in others the change is much less complete. Within this belt of crystalline rocks, Proterozoic formations are believed to occur, but they have not been generally differentiated from the Archean on the one hand, and from the metamorphic Paleozoic rocks on the other.

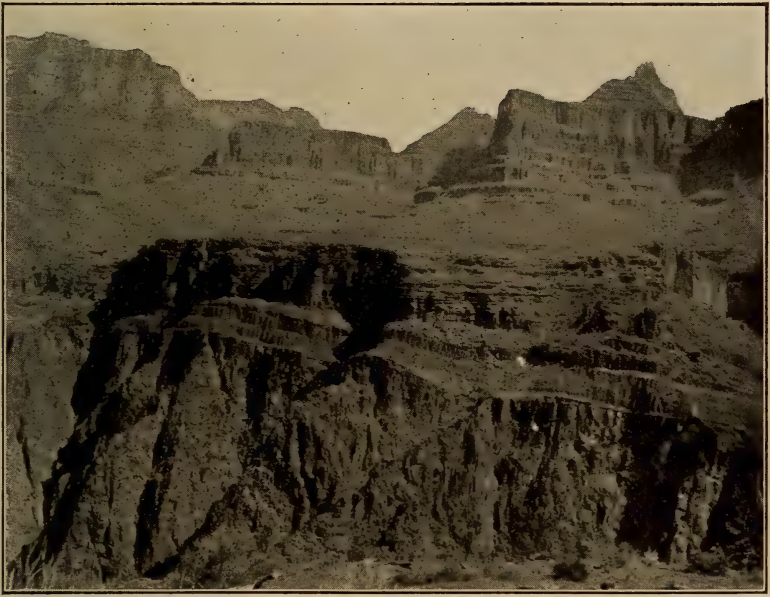

Fig. 88.—Figure showing the Archean, Proterozoic, and later formations at one point in the Grand Canyon of the Colorado in northern Arizona. The lowermost non-stratified formation is Archean. The horizontal beds in the upper part are Paleozoic, their basal portion being Cambrian. The tilted beds between the Archean and Paleozoic are Proterozoic. (Atwood.)

In the Green mountains of Vermont, there appear to be two series (the Mendon and the Mount Holly) of sedimentary or meta-sedimentary rocks of complicated structure, unconformable beneath the Cambrian.[1] Patches of pre-Cambrian rock are known in thirteen places in western Massachusetts, but they are separated with difficulty from the Cambrian, Silurian, and Devonian beds which were metamorphosed with them. They consist of gneisses, schists, and crystalline limestone [2] (Fig. 89). In southeastern New York there appear to be pre-Cambrian metamorphic rocks of complicated structure (Fordham gneiss) closely associated

[1] Whittle, cited by Van Hise, 16th Ann. Rept. U. S. Geol. Surv., Pt. I, p. 827.

[2] Ibid., p. 830; and Emerson, Holyoke, Mass., folio, U. S. Geol. Surv.

with metamorphic rocks of lesser age.[1] In places the gneiss is partly of sedimentary and partly of igneous origin, developed by the parallel injection of granitic materials into a sedimentary series.[2] The crystalline rocks of the Highlands of northern New Jersey[3] appear to be chiefly Proterozoic. They include both igneous and sedimentary rocks. Among the latter are limestone (marble), graphitic gneisses, and large bodies of iron ore, all of which point to the existence of life at the time the beds were deposited. In the South Mountain district of Pennsylvania the Proterozoic seems to be represented by igneous rocks on which the Cambrian rests unconformably. In no one of the foregoing localities has the Archean system been certainly identified, nor has the Proterozoic age of the rocks been generally fixed with certainty.

Similar formations in similar relations exist in the Piedmont plateau of Maryland,[4] where there is an eastern belt of crystalline rocks which are thought to be Proterozoic (though perhaps including some Archean), and a western belt less completely crystalline which are thought to be Paleozoic. In western North Carolina[5] there is a series of meta-igneous rocks classed as Algonkian. They consist of meta-diabase, epidotic and chloritic schist (probably altered basalt), dark schists, and meta-rhyolites (altered from acidic glassy rocks). All are more or less metamorphic, and some of them highly so.

Farther southeast is a great area of crystalline rocks occupying parts of Virginia, North and South Carolina, Georgia, and Alabama, formerly referred to the Archean. In this group of rocks, strata as young as the Ordovician are known to occur, though the great body of the rock is probably older. Within the group, Proterozoic rocks are believed to occur, though they have not been differentiated. Archean rocks have not been certainly identified.

While the correspondence of the Proterozoic rocks in these various regions with those of the Lake Superior region is not generally very close, it may be pointed out again that close correspondence is not to be expected, even if the rocks of different localities were contemporaneous in origin. The phases of sedimentation taking place about any land mass at any time are largely dependent upon the height of the land, the freeness of the exposure of its coasts, the amount of precipitation, the climate, and the character of the formations suffering erosion. These various factors were as likely to be dissimilar about the various centers of sedimentation, as to correspond. Igneous rocks form a not inconsiderable part of the Proterozoic systems, and there is no law requiring igneous activities in different regions to correspond either in time or in the nature of their products. Even body deformations, which are much the most general and which are the basis for the subdivision of the systems, need not have corresponded in their particular phases, in different regions. It follows (1) that the number of series within the Proterozoic in one place may not be the same as in another; (2) that the thicknesses of the various systems may vary within wide limits; (3) that there need have been no close correspondence in the sorts of rock in different regions at the outset; and (4) that they may have been metamorphosed unequally since their deposition. The dissimilarity of the Proterozoic in different regions, as suggested by the preceding sketch, was, therefore, to have been anticipated.

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[1] Ibid., p. 834, and Merrill, N. Y., folio, U. S. Geol. Surv.

[2] Van Hise, op. cit. p. 836.

[3] Wolff. See Repts. of U. S. Geol. Surv., especially those for 1893 and 1896; and Wolff and Brooks, 18th Ann. Rept. U. S. Geol. Surv., and Bull. Geol. Soc. Am., Vol. VIII, p. 397.

[4] Van Hise, op. cit.; Bascom, Md. Geol. Surv. Rept. on Cecil County, 1902. This volume also gives a review of previous study, and bibliography (pp. 49–62) of the literature touching this area; also Keith, Harper's Ferry, Va.-Md.-W. Va. folio

[5] Keith, Cranberry, N. C.-Tenn. folio, U. S. Geol. Surv.

Proterozoic Formations in other Continents.

Little need be said of the Proterozoic systems of other continents, but they are believed to exist in Great Britain,[1] where the Torridonian sandstones (8,000–10,000 feet thick in Scotland) and perhaps the Dalradian series may be Proterozoic; in France,[2] where phyllites, graywackes, quartzite, sericitic schists, and igneous rocks with an aggregate thickness of several thousand meters, are regarded as Proterozoic; in Spain, where phyllites, hälleflinta, and quartzite represent the era; in Germany, where mica schists predominate below, and phyllites above;[3] in Finland,[4] where nearly 3000 meters of conglomerates, quartzites, schists, limestone, and diorite lie between the Archean and the Cambrian; in Scandinavia (Sweden), where there are similar thicknesses of similar rocks occupying a similar stratigraphic position; and probably in India and Brazil. In more than one of these countries, the pre-Cambrian sedimentary rocks are thought to belong to at least two systems, separated by unconformities. It is worthy of note that in Sweden[1] iron ore occurs, as in the Huronian of Lake Superior. Little has been done toward the correlation of the pre-Cambrian rocks of Europe and America. It is significant, however, that the terms Algonkian and Proterozoic are being adopted[2] in the delineation of the pre-Cambrian formations on geological maps. As in America, the Proterozoic rocks of Europe contain occasional fossils, though their number is small.

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[1] Sir Archibald Geikie, Jour. of Geol., Vol. I, and Text Book of Geology, 4th ed., Vol. II.

[2] DeLapparent, Traité de Geologié.

[3] Gümbel, Grundzüge der Geologie, pp. 511–522.

[4] Sedersholm, Ueber eine archäische, Sedimentformation in südwestlichen Finland, Bull. de la Commission Geologique de la Finlande, No. 6, 1897.

In the province of Shan-si, China, there are at least two great Proterozoic systems, separated by an unconformity. The lower system is composed of meta-sedimentary rocks, closely folded; the upper is somewhat folded and slightly metamorphosed. The lower system rests on the Archean, and the upper underlies the Middle Cambrian unconformably.[3]

Life During the Proterozoic Era.

While the Proterozoic rocks do not generally contain fossils, there can be no doubt that life existed during the era. The direct evidences are as follows: (1) The carboniferous shales, slates, and schists indicate the existence of life; (2) the occasional fossils[4] (especially in Montana and in the Grand Canyon of the Colorado in Arizona) demonstrate the existence of life at that time; (3) the iron ore of these systems, although not originally deposited in its present form, seems to imply the existence of life, both when it was accumulated, and when it was transformed into its present condition; and (4), the limestone. It should be noted that limestone occurs in the Huronian system, and that it is, in some places, near its base. The limestone was formerly regarded as demonstrative of the existence of life, but in recent years the belief has gained ground that considerable formations of limestone may have originated by precipitation from sea-water. This origin is suspected for many limestone formations which are free from fossils, and if this hypothesis is applicable to any extensive formation of limestone, it may be applicable to those of the Proterozoic systems. But even without reliance on the limestone, the fossils leave no doubt of the existence of life in the Proterozoic era.

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[1] Törnebohm, Grunddragen af det Centrale Skandinaviens Bergbyggnad, 1896.

[2] Bäckström, Vestanafältet (The Vestana region), 1867.

[3] Willis and Blackwelder, Carnegie Institution. Unpublished data.

[4] For summary of knowledge concerning pre-Cambrian fossils, see Walcott, Bull Geol. Soc. Am., Vol. 10, pp. 199-244.

The best-preserved fossils are those of eurypterus-like crustacea. There are also tracks of two genera of annelids, and other undetermined forms. Besides these certain fossils, there are obscure forms which appear to be referable to brachiopods and pteropods. It is significant that the oldest definite fossils yet found are well-developed crustacea, forms well up in the animal kingdom.

CLIMATE.

Since inferences concerning the climate of any period are drawn chiefly from fossils, and since fossils are exceedingly rare in the Proterozoic strata, there is little warrant for any conclusion concerning the climate of the period. Certain pre-Cambrian conglomerates of Ontario, shown in the Cobalt region and elsewhere, have been interpreted recently, as of glacial origin, but the evidence thus far presented does not seem to be conclusive on this point.

[1] Coleman, Geol. Soc. Am., 1906.

CHAPTER V.

THE CAMBRIAN PERIOD.

Formations and Physical History.

The great crustal movements which brought the Proterozoic era to a close converted a large area within the limits of the North American continent into land. This is shown by the geographic distribution and the stratigraphic relations of the next succeeding system of sedimentary rocks. This system, *the Cambrian,*[1] is the oldest system of rocks now recognized as having been deposited during the Paleozoic era.

Where the base of the Cambrian system in North America is accessible, the system is, as a rule, unconformable on underlying formations (Figs. 88 and 89). Where this is the case, it is inferred that the surface on which it rests was a land surface and exposed to erosion for a time before the formations above the unconformity were deposited. Furthermore, the attitude of the Proterozoic strata is such as to show that they were locally much disturbed prior to the notable erosion which preceded the deposition of the Cambrian beds (Fig. 89).

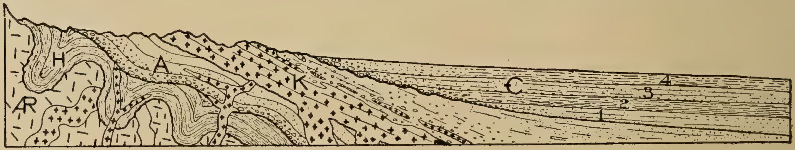

Fig. 89.—Diagram representing the general relations between the Cambrian, Ꞓ, and the Proterozoic formations. The diagram is based on the general relations which exist in the Lake Superior region.

Were the total area where the Cambrian system is unconformable on its base known, it would furnish a basis for estimating the extent of the withdrawal of the sea from the continent at the close of the Proterozoic era, and before the deposition of the known Cambrian. If it were possible, on the other hand, to determine the exact area once covered by formations of the Cambrian system, this determination

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[1] A summary of the literature on the North American Cambrian prior to 1892 is given by Walcott in Bull. 81, U. S. Geol. Surv.

It is no longer possible to procure this map

would give the maximum area covered by the Cambrian seas, for the Cambrian formations were, so far as known, laid down on the floor of the sea. If the exact area of the sea at any stage of the Cambrian period were determined, the exact area of the land at the same stage would obviously be known. If these data could be determined for each stage of the period, they would constitute the record of its geographic changes, so far as distribution of land and water is concerned. These determinations cannot be made for every stage of the period, but approximations may be made for certain stages, and these approximations give a valuable insight into the geography of the times.

THE SUBDIVISIONS OF THE CAMBRIAN AND THEIR DISTRIBUTION.

The Cambrian period has been, for convenience, divided into three parts, which may be called the Earlier, the Middle, and the Later divisions. The system of rocks deposited during the period has been divided into three corresponding series, known as the Lower, Middle, and Upper Cambrian respectively. Other names are sometimes assigned to these divisions. Thus Georgian (Vt.), Acadian, and Potsdam (N. Y.), names of localities where the corresponding divisions of Cambrian were first carefully studied, are synonyms for Lower, Middle, and Upper Cambrian respectively, as these terms are used in North America. Saratogan[1] and St. Croix[2] are also used as synonyms for Potsdam. The approximate distribution of the beds of sediment laid down in each of the three divisions of the period is known, and the variations in the distribution of the three series record the changes in the relations of land and water during the Cambrian period.

The Lower Cambrian.

Distribution.—Fig. 90 shows the known surface distribution of the Lower and Middle Cambrian (Georgian and Acadian) series. The black portions represent the areas where these series come to the surface. The parts shaded with lines represent the areas within the limits of the continent where the same series are believed to occur, though now buried. The longer the lines, the better the basis for the inference that one or both series are present. North of Mexico, the unshaded areas shown in the figure are thought to represent approximately the

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[1] Recently proposed by the U. S. Geol. Surv., 24th Ann. Rept., p. 27, to take the place of Potsdam.

[2] Not much used except in Minnesota.

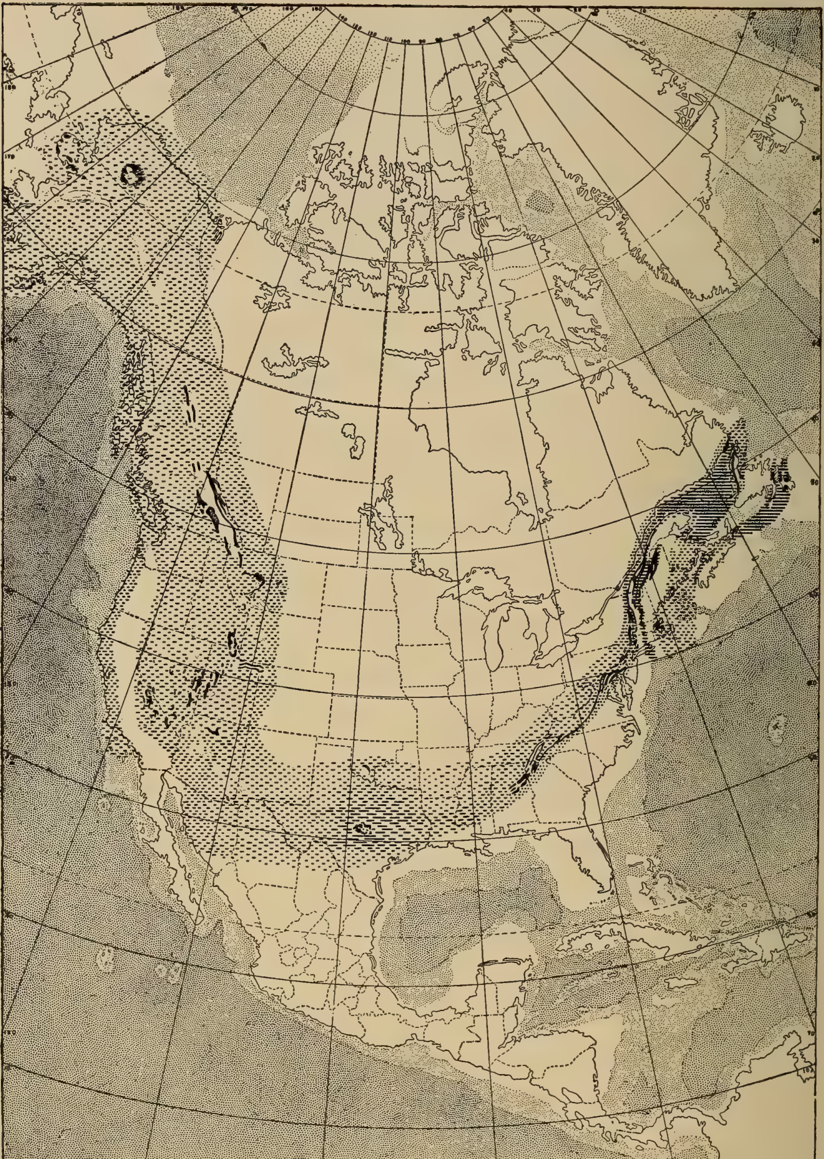

FIG. 90.—Map showing the outcrops (in black) of Early and Middle Cambrian formations. The areas shaded by lines represent regions where the formations are believed to exist, though not exposed. The longer the lines, the better the basis for belief in the existence of the beds. The unshaded areas north of Mexico are believed to have been land during the early portion of the Cambrian period. The unshaded area south of the United States represents lack of knowledge. The shading within the area of the ocean is the same as in Fig. 38.

areas which remained above the sea up to the end of the Middle Cambrian. In Mexico and Central America, the blank area represents lack of knowledge. Since the distribution of the Lower and Middle Cambrian series is much the same, the black areas of the map may be taken to represent the surface distribution of the Lower Cambrian without serious error, if the areas in Arizona, Oklahoma, and Texas be excluded. On account of later erosion, the Lower and Middle Cambrian strata are probably not now present over the whole of the area on which they were originally deposited.

So far as these formations contain marine fossils, it is safely inferred that the areas where they now occur were occupied by the sea at some time during the early and middle portions of the Cambrian period.

As the map shows, the Lower Cambrian is known on the coast of Labrador, in Newfoundland, at various points between these localities and Maine, at several places in New England, at many points in the Hudson-Champlain valley, and at various points in the Appalachian mountains between the Hudson and Alabama, but is generally absent from the area east of these mountains. From the distribution of the Lower Cambrian series in the east, and from its fossils, it is inferred that a great sound existed in early Cambrian time near the southeastern border of the continent, extending from Labrador to Alabama.[1] This sound is believed to have been shut off from the Atlantic by land which occupied a large part of the site of the present Piedmont plateau, but whose eastern limit is unknown.

Lower Cambrian formations, with fossils of marine organisms, are also known in Nevada, Utah, western Montana, Idaho, and in some parts of British Columbia, from which it is likewise inferred that the sea occupied portions of western North America during the same epoch.

The absence of Lower Cambrian strata from other regions is hardly less significant than their presence in those mentioned. They are believed to be wanting in most of Montana, in Wyoming, Colorado and Arizona, and in the territory east of these states nearly to the Appalachian mountains.[2] Not only are they absent now, but they appear never to have been present, and this leads to the inference that most of the great area between the Appalachian mountains on the east and the Rocky mountains on the west was above the sea during the early part of the Cambrian period.

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[1] Ulrich and Schuchert, Bull. 52 (Paleontology 6) New York State Museum, Report of the State Paleontologist, 1901, pp. 635–6.

[2] Comstock (First Ann. Rept. Geol. Surv. of Texas, 1889, pp. 285–292) thinks Lower Cambrian occurs in Texas.

Geography of the Early Cambrian.—On the basis of the known distribution of the Lower Cambrian strata as cited above, it is inferred that there was an extended land area within the limits of North America in the early part of the Cambrian period, and from the widespread unconformity of the Lower Cambrian on its bed, it is inferred that this area was still more extensive just before the deposition of the known Lower Cambrian. The map (Fig. 90) shows, as nearly as it is now known, the area of land and water within the area of North America during the early part of the period.

"Lost" interval.—Where the Cambrian is unconformable on pre-Cambrian formations there is a break in the geological record. Such breaks are sometimes said to represent "lost" intervals, the intervals which are "lost" being the periods elapsing between the deposition of the beds below the unconformity, and those above. This designation for such an interval is only partly true, for in the unconformity itself there is the record of exposure and erosion, followed by submergence and deposition. The general sequence of events is evident, and to this extent the record is not lost. On the other hand, the products of the recorded erosion were deposited elsewhere, constituting a new formation. Wherever the sedimentary beds deposited during the erosion interval represented by an unconformity are buried, the record of the interval is certainly not open to inspection. It may be regarded as "lost," or as too well preserved.

The relations and principles involved are illustrated by Figs. 91 to 93. Let the line *AA′*, Fig. 91, represent the sea-level at the beginning of the uplift which closed the Proterozoic era, while *CC′*, Fig. 92, represents the same level at the time of maximum post-Proterozoic uplift. While the water-level was changing from *AA′* to *CC′*, sedimentation was in progress beneath the water at all stages, and at all stages the sedimentary beds were essentially conformable on the formations below. So long as the sea-level stood at *CC′*, deposition still continued to the right of *C*, the beds being conformable on their substratum (1, Fig. 92).

Later, as the stratigraphic relations of the Lower Cambrian formations show, the sea again advanced on the land, and as the shore line was shifted from *C* toward *A* (Fig. 92), sediments were in process of deposition on the surface which had recently been land, but which was now submerged. The deposits made at this stage between *C* and *A*, Fig. 93, were unconformable on the formations beneath, though the corresponding deposits to the right of *C* were conformable on their base. It is manifest that the unconformity between formations *Al* and 2 (Fig. 93) must represent a longer interval of time between *B* and *A* than between *B* and *C*, since the formation *Al* had been longer exposed in the former region. From *A* to *C* the section records a "lost" interval, but the deposits made during this interval (1, Fig. 93) are preserved to the right of *C*, though they may be inaccessible.

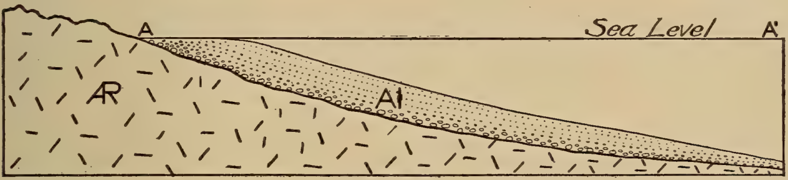

FIG. 91.—Figure showing a series of sedimentary rocks, *Al*, resting on and against older rock, *Æ*.

In the case under consideration, *Al*, deposited before the uplift, stands for the whole of the Proterozoic (Algonkian). As a matter of fact, the structure of the Proterozoic is much more complex than these figures show. (See Fig. 89.) Formation 2 (Fig. 93) is Cambrian. Formation 1, being inaccessible, is not classified. Were it accessible, its classification as Cambrian or as Proterozoic would probably depend on its fossils. Looked at from the physical point of

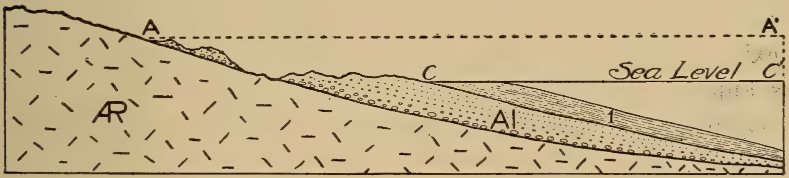

FIG. 92.—This figure represents the region shown in Fig. 91 as having risen, or the sea-level as having been lowered. Erosion has affected the upper portion of the formations represented by *Al*. Meantime deposition of the eroded material has taken place beneath the sea-level. These new deposits are represented by 1 in the figure.

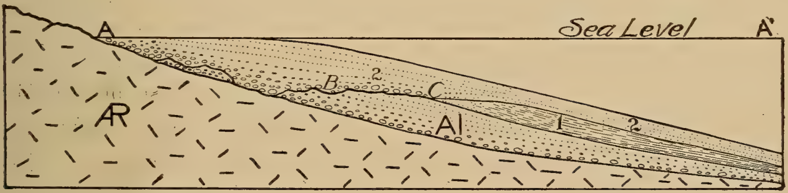

FIG. 93.—This figure represents the same region as Figs. 91 and 92 after the land has sunk so as to allow the sea to regain approximately the position which it occupied in Fig. 91. Younger sediments, 2, have buried the older, 1. The formation represented by 2 is unconformable on *Al* and on *Æ* but comformable on 1.

view, the question is, Shall the Proterozoic era be regarded as ending, so far as this region is concerned, (1) when the uplift preceding the Cambrian began, (2) when it reached its maximum, or (3) when the subsequent subsidence was inaugurated? To this question no categorical answer can be given, and formation 1 of Fig. 93 may be looked on as representing the time of transition from the Proterozoic to the Cambrian.

Extent of unconformity at base of Lower Cambrian.—Except in the northwest, the Lower Cambrian is generally unconformable on deformed beds of Proterozoic age, but it seems certain that the Lower Cambrian must be conformable on the Proterozoic in areas which were continuously under water (1) during the later part of the Proterozoic era, (2) during the generally unknown interval between the Keweenawan and Cambrian, and (3) during the Cambrian. Since it is improbable that the larger part of the area which was receiving sediment during the last period of the Proterozoic era became land at the end of that era, it follows that areas where conformity exists between Cambrian and Proterozoic are probably more extensive than areas where unconformity exists. From a study of the relations suggested by Figs. 91 to 93 it is apparent that unconformity between Proterozoic and Cambrian is likely to be most general just where their contacts are most frequently seen.

The Middle Cambrian.

The strata of the middle division of the Cambrian (Acadian) are known to occur in the same general localities as those of the lower, both in the eastern and western parts of the continent, and in addition, they occur in Texas, Oklahoma, Indian Territory,[1] Arizona,[2] and in some parts of Montana,[3] and possibly even in the western part of Wisconsin[4] where Lower Cambrian is absent, or at any rate not known. This distribution indicates that the interior was being invaded by the sea from the south and southwest before the close of the Middle Cambrian epoch. Like the preceding series, the Middle Cambrian beds are generally absent from the eastern interior. Where the Middle Cambrian rests on the Lower, as in the east and west, the two series are generally conformable.[1] Where it rests on pre-Cambrian formations, as in the States mentioned above, it is in unconformity with them. (Figs. 88 and 89.)

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[1] Taff, Professional Paper No. 31, U. S. Geol. Surv.

[2] Blake, Am. Geol. Vol. XXVII, p. 162; Walcott, Bull. Geol. Soc. Am., Vol. X, p. 217.

[3] Walcott, idem., p. 209.

[4] Walcott, idem., p. 224.

The Upper Cambrian.

In the Later Cambrian (Potsdam, Saratogan) epoch, the Appalachian region on the one hand, and the Cordilleran region on the other, were still submerged, as shown by the conformable (in general) superposition of the Upper Cambrian beds on the Middle Cambrian, in both regions. In addition, the Upper Cambrian beds are spread widely over the interior of the continent, indicating that the sea had extended itself greatly at the expense of the land in the Potsdam epoch. Where the Upper Cambrian rests on pre-Cambrian formations, it is in unconformity with them.

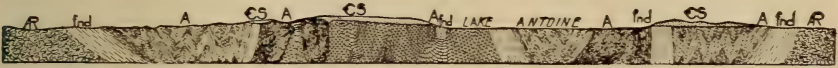

Fig. 94.—This figure represents a section in the Menominee region of northern Michigan, and shows the Potsdam sandstone, *Ꞓs*, in unconformity with Proterozoic formations, *A*. *Æ*, Archean. (Van Hise, U. S. Geol. Surv.)

Fig. 95 shows something of the distribution of the Upper Cambrian series. The black areas represent the areas where the series comes to the surface; the areas lined horizontally represent the areas where it is confidently believed to be present, though buried; the areas shaded by dashes are the areas where the series is probably present; while the dotted tracts represent the areas from which the series is thought to have been removed by erosion. The blank areas, except in Mexico and Central America, stand for the tracts which are thought to have remained above the sea throughout the Cambrian period;[2] in those countries, they represent lack of knowledge.

SECTIONS OF THE CAMBRIAN AND THEIR INTERPRETATION.

Fig. 96 represents known sections of the Cambrian formations in various localities.[3] The study of these sections, while involving

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[1] Ulrich and Schuchert think that the Appalachian synclinorium of Early Cambrian time was largely drained at the close of that epoch. Loc. cit., p. 636.

[2] Since this map was prepared, Upper Cambrian beds have been reported from southwestern Texas. Richardson, Reconnaissance in Trans Pecos, Texas, Bull. 9. Univ. of Tex. Min. Surv.

[3] Walcott, Bull. 81, U. S. Geol. Surv.

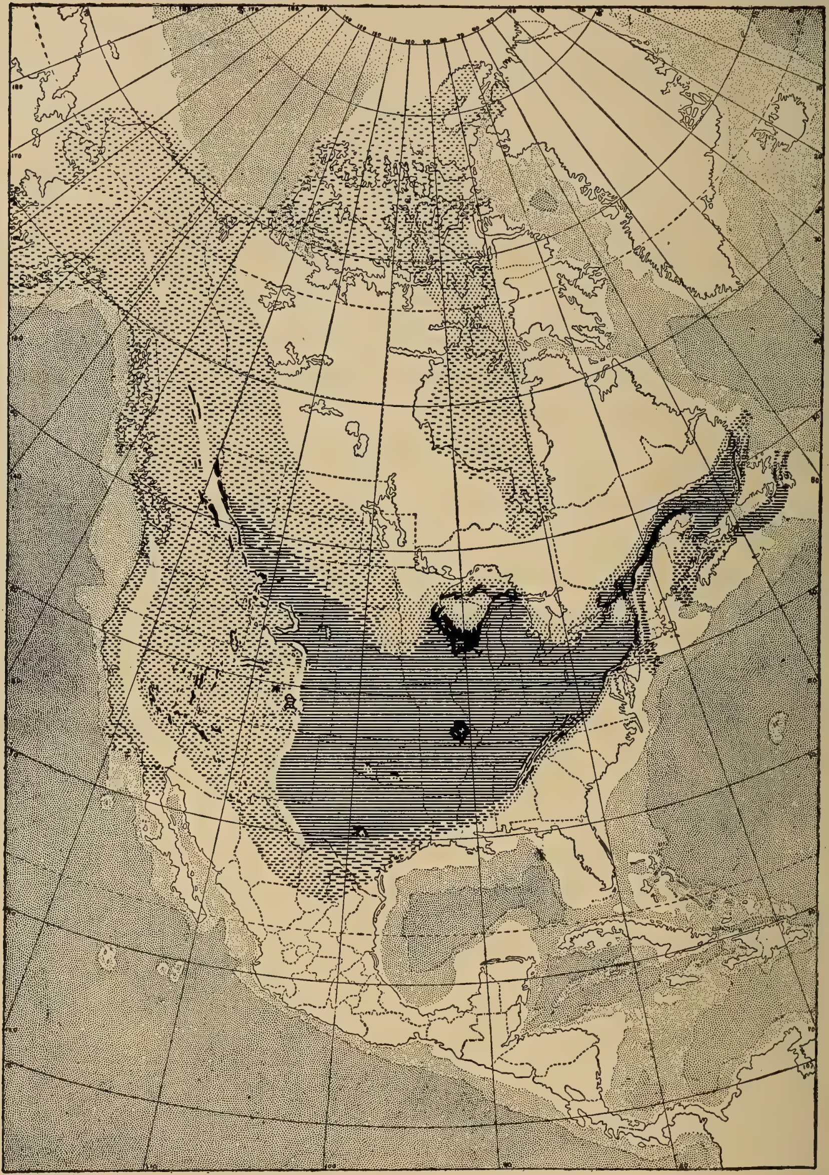

FIG. 95.—Map showing the Upper Cambrian formations. The outcrops are shown in black. The continuous lines represent areas where the Upper Cambrian formations are confidently believed to exist, though concealed. The dashes represent areas where there is some reason for believing them to exist. The dotted areas represent areas from which the Upper Cambrian is believed to have been removed by erosion. The unshaded areas have the same meaning as in Fig. 90.

some repetition of what has been said, will help to make clear the method by which the geography (and therefore the geology) of the successive stages of the Cambrian is made out. If, for example, sections 1 and 2 be compared, it is seen that in both cases the three divisions of the Cambrian system are present, and that in both cases the Lower Cambrian rests unconformably on the Proterozoic, while the Middle rests conformably on the Lower, and the Upper on the Middle. From these two sections it is inferred that the Cambrian seas covered the two localities where these sections occur, during at least the later portion of the Early Cambrian, during the Middle Cambrian, and during at least the earlier portion of the Later Cambrian epoch. These sections do not indicate how much of the Upper Cambrian in these two areas has been removed by erosion. From the strict conformity of the three groups of strata, it is probable that the Middle Cambrian beds are present in their full thickness in both sections; that is, that both localities were under water continuously in the Middle Cambrian epoch, and that none of the Middle Cambrian series has been lost by erosion.

It will be noted that the Lower Cambrian in section 1 is much thinner than that in section 2. This might be explained in either of two ways. (1) In the area of section 1, the Proterozoic (Algonkian) surface may have been above water during a part of the Lower Cambrian epoch. If this be true, the land at this point must have sunk so as to let the sea cover it before the close of the epoch. If the area of section 2 was under water longer during the early Cambrian epoch, the greater thickness of the Lower Cambrian in this section would be explained. (2) The other possible explanation of the inequality is found in the unequal rates of accumulation of sediments. So far as the sections show, both areas may have been under water during the whole of the Georgian epoch; but if the rate of sedimentation was slower at 1 than at 2, the thickness of strata would be correspondingly less. From the sections it is not possible to decide between these alternative explanations.

If section 2 be compared with section 3, a somewhat different relation is shown. In the latter, the Lower and Middle Cambrian are both present, while the Upper Cambrian is wanting. This again might be explained in either of two ways. Either eastern Massachusetts rose above sea level after the Middle Cambrian epoch, so that the Upper

Cambrian strata were not deposited there, or the Upper Cambrian beds, once deposited, have since been removed by erosion. Between these alternatives the figure does not decide.

If section 3 be compared with section 4, it will be seen that the latter lacks the Middle Cambrian as well as the Upper, the Lower resting, as before, unconformably on the Proterozoic. This section might mean either that the area where it occurs emerged from the sea before the Middle Cambrian epoch, or that such Middle and Upper Cambrian beds as were once deposited there have since been carried away by erosion.

From section 7 it is seen that the Lower Cambrian of eastern New York has extraordinary thickness, compared with the areas farther northeast. As in the case of sections 1 and 2, this may mean either that the reign of section 7 was under water longer during the Early Cambrian epoch, or that sedimentation was here more rapid. The rapid rate of accumulation might be accounted for in more than one way. If the area of section 7 was near a coast, and especially if the adjoining land was high, rapid sedimentation would be likely to follow. If at the same time the formations of the land were easily eroded, the rate of sedimentation would be still further increased. Rivers may have come into the sea in this vicinity with heavy loads of sediment, or shore currents may have been such as to allow of exceptionally rapid accumulation of sediments at this point.

The Upper and Middle Cambrian of section 8 are somewhat thinner than the corresponding series in sections 1, 2, and 6. So far as the Upper Cambrian is concerned, the thinness might be due to the removal of its upper part by erosion; but the thinness of the Middle Cambrian, taken together with its conformity above and below, seems to indicate that the accumulation of sediment was here relatively slow during this epoch. The study of the various sections may thus be made to throw light upon the conditions which existed at the points where sections are known.

In the areas where sections 1 to 11 and 13 to 17 occur, the Lower Cambrian strata are present. This means that the Lower Cambrian seas covered these areas. On the other hand, sections 18 to 28 suggest, by the absence of the Lower Cambrian formations, that the sea did not occupy the areas where these sections occur in the Lower Cambrian epoch. The only alternative is that the Lower Cambrian rocks

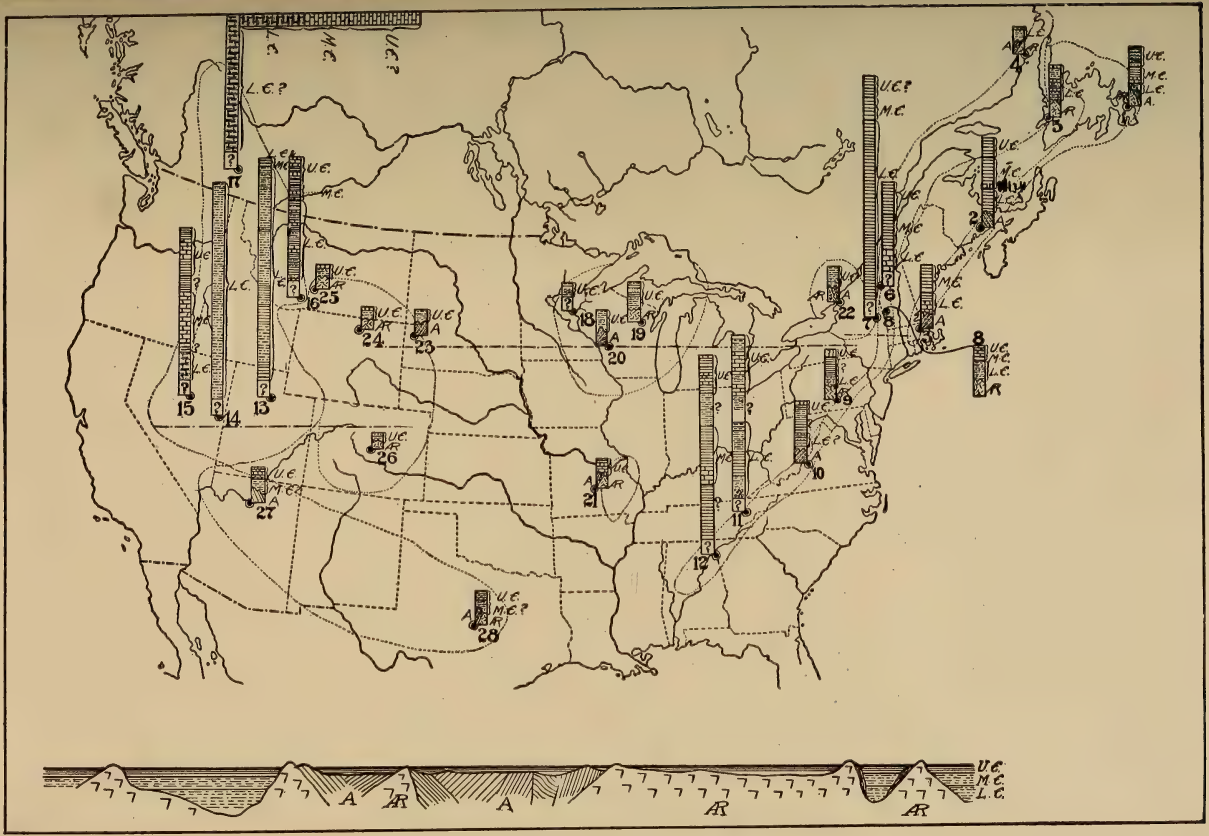

FIG. 96.—A map showing various sections of the Cambrian formations. Æ=Archean, A=Proterozoic (Algonkian), LꞒ=Lower Cambrian, MꞒ=Middle Cambrian, and UꞒ=Upper Cambrian. (After Walcott, U. S. Geol. Surv.)

once covered this area, but were subsequently removed by erosion before the Potsdam epoch, an alternative for which there appears to be no warrant. Sections 27 and 28 show Middle Cambrian strata resting on Proterozoic or Archeozoic rock, thus indicating that the Middle Cambrian sea covered the localities of these sections, although the Early Cambrian sea did not. Sections 18 to 26 show the presence of Upper Cambrian beds only, and therefore give some clue as to the extent of the advance of the sea upon the land in the Upper Cambrian epoch.

Interpretations.

Interpreting these sections, it is inferred that in the early part of the Cambrian period the sea covered some parts of the eastern border of the present continent as far south as Massachusetts, that it occupied a narrow, strait-like belt along the Appalachians, that it was also present in the west, but that the great interior was, for the most part, land (Fig. 90). From the same data it is inferred that during the Middle Cambrian epoch the sea encroached on the interior from the south and west, reaching western Montana, Arizona, and Texas during the Middle Cambrian epoch (Fig. 96). Still later, in the Potsdam (Saratogan) epoch, the sea gained dominion over the land until, at its close, a large part of the area of the United States was beneath the sea (Fig. 96).

Theoretically, this result may have been brought about by a rise of the sea, or by a lowering of the land, or by both together; or, changing the point of view somewhat, it may have been brought about by a deep-seated deformation of the earth's body, or by superficial changes, whether gradational or deformational, or by both combined. It may not be best to try to reach final conclusions where the subject is so intricate and the data so imperfect as in this case, but it is well to weigh the considerations that favor one or another of the possible participating agencies and to try to discriminate between the work of the inevitable agencies and that of the more or less uncertain ones.

There is need to discriminate at the outset between two classes of deformation. The one is that which has just been called *body deformation,* whose origin is presumed to be internal, while the other, which will be defined below, is *superficial deformation,* and more or less independent of internal forces at the time of its accomplishment.[1] As will appear presently, *superficial deformations* are not excluded by the general evidence against profound deformations. In the present case we may first inquire how far gradation and allied agencies may have been effective in bringing about the transgression of the sea over a large part of the American continent in the later part of the Cambrian period. We may inquire next how far superficial deformations may have coöperated with gradation in bringing about the transgression of the sea; and then, if these seem inadequate, we may resort to the more hypothetical forces that reside in the deeper body of the earth.

(1) **How far may gradation have been competent to bring about the submergence of the continent?**—Gradation is perpetual and inevitable where land and sea exist. The waves attack the land along its borders, and the familiar agents of degradation reduce its surface. The former is a direct cause of the encroachment of the sea upon the land, and the latter an indirect one, since all sediments transported from the land and deposited beneath the sea displace an equal volume of water, and correspondingly raise the sea surface. Small as this rise must have been for any brief period, its effect was to cause the sea to advance upon the land. The lowering of the land by degradation at the same time, facilitated the advance. *If continued long enough*, this coöperative process of shore-cutting around the borders of the lands, of down-cutting over the whole surface, and of uplifting of sea-level, must inevitably have caused the water to cover the whole continent and to spread deposits over all but the last remnants of it, *provided there was no deformation of the body of the earth in the meantime.* This familiar process is illustrated in miniature in Vol. I, pp. 60–62, where the lifting of the sea-level is neglected, because infinitesimal in that case. Since this complex process is inevitable, it is well to assign to it whatever it is competent to do consistently with the results of other agencies known to have been in operation at the same time.

It has been computed that if the earth, in its present condition, were to remain without deformation for the requisite period, the erosion of the continents and the transfer of the material to the sea would raise the sea-level about 650 feet (Vol. I, p. 545). The last remnants of the continents to be submerged by this process would, therefore, stand at that height above the present sea-level. The disturbed condition of the Proterozoic formations, and the truncated condition of their upturned beds, may be taken as good evidence that the continents stood forth from the sea rather prominently at the close of the Proterozoic era. The actual mass of the continents is not known, and it is not very essential for present purposes. The higher the continents, the more the material available for removal to the sea and so for the lifting of the surface when deposited beneath it, and the more the lifting needful to submerge the continents; while the lower the continents, the less the material available for lifting the sea, and the less lifting needful to cause it to cover the land. It is a case of reciprocal relations and of mutual accommodation, in any event. The result is certain in any case, if the time be long enough and *deformation does not interfere.* Deformation is a possible bar, as well as a possible aid, to the wide spreading of the sea on the land. A satisfactory explanation of the covering of great tracts of land by the sea may therefore require the exclusion, or the limitation, of profound crustal movements, rather than their participation.

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[1] For the general treatment of these two phases of deformation, see Vol. I, pp. 548–589, and this Vol., pp. 119–132.

The direct evidence of gradation in the Cambrian period is clear and firm, for there is no ground to doubt that the main body of the Cambrian sediments was eroded from the land and deposited in the sea. This gradation tended to lower the land and raise the sea. We are safe, therefore, in concluding that surface action was a participant in the result attained. There is much evidence that considerable progress was made toward the base-leveling of the American continent, and of other continents as well, before the close of the Cambrian period. The very fact of the spreading of the sea so widely over the interior of a continent, and of the laying down of a relatively uniform and not very thick formation of sandstone over such broad areas, on a surface which approached a plane, though underlain by beds which are commonly much deformed, is in itself evidence of extensive leveling by degradation.

Now base-leveling *implies a nearly undisturbed attitude of the land and sea* during its progress, and hence in itself favors the view that no *great* deformation affected the continent while it was going on. In harmony with this view, there is an absence of direct evidence of a profound deformation during the Cambrian period. There is therefore a presumption in favor of gradation and against body deformation during the period, and good practice in interpretation leads us to inquire how far the former may have been the cause of the submergence of the continent, before we resort to the doubtful expedient of invoking profound deformation.

If gradation were the *sole* agency involved in the submergence of the lands, the advance of the sea should have been systematic, though not necessarily equal in rate or extent at all times and places, and along this line a means may be found of judging how far this agency was a real one. Without attempting to make a full application of this test here, it seems certain that there were some shiftings of the areas of deposition other than those which might have arisen from a simple gradational advance of the sea upon the land, and that there are specific evidences of warping, as implied by the differences in the depth of the deposits and in their characters and relations to one another, as brought out in the previous descriptions. None of these warpings were, however, of the more intense and declared type, such as occurred repeatedly in the Proterozoic and Archeozoic eras. Those which are now known were of a relatively gentle type, and limited in amount and in prevalence. These characteristics of the Cambrian deformations lead to inquiry under the second head.

(2) **How far may superficial deformation have contributed to the submergence of the lands?**—(*a*) *Lateral spreading.*—The continental platforms now stand forth above the ocean bottom as great plateaus. They may be roundly estimated to rise 15,000 feet above their true sub-oceanic base. Their weight develops a pressure on their basal parts that may safely be estimated at 15,000 to 20,000 pounds to the square inch.[1] This pressure *tends to cause the platforms to spread by lateral creeping.* This is opposed by the strength of the rock, and by the hydrostatic pressure of the oceans against the sides of the platforms. If this last be estimated at 5000 pounds per square inch at the bottom, there remains an unbalanced pressure of 10,000 to 15,000 pounds per square inch. Even the lesser of these figures is equal to

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[1] For rough computations where exact accuracy is immaterial, it is convenient to remember that a cubic foot of rock weighs about as many pounds as there are square inches in its base, though usually somewhat more. Hoskins, in his computation of the strength of domes (Vol. I, p. 581), takes 180 pounds as the weight of a cubic foot of firm crystalline rock of the granitic type. $180 \div 144 = 1.25$. At 2.7 sp. gr., a cubic foot weighs 167 lbs. $167 \div 144 = 1.16$.

the crushing strength of some of the weaker rocks, and is a notable percentage of the crushing strength of even the strongest ones. Under less pressure than this, rocks are often observed to creep, as in mines and canyons. It is not improbable, therefore, that a pressure of this magnitude, constantly exerted for a prolonged period, might cause some spreading of the great continental platforms, and hence (1) some lowering of their surfaces, and (2) at the same time some rise of the sea-level.

Such a force, perpetually in readiness to act, if not actually producing movement, would always coöperate with any other agency that tended to work in the same direction, or to develop weakness in the resisting power of the continental mass. Coöperating with the molecular changes concerned in rock alteration, this pressure would tend to give the rocks lateral extension in the line of least resistance. Whether it is really very effective or not, it is at least a constant agency *tending* to produce lateral creep, and hence to cause a lowering of the surface of the continents, a rise of the surface of the sea, and therefore a spreading of the ocean waters.

We have considered this point on the basis of the present relative heights of the continents above the ocean floor. A little consideration will show that we are not likely to be far in error in applying similar figures to the Cambrian continents, for if the volume of the ocean was then not far from what it is to-day, the ocean basins must have had much the same capacity as now, and as the continental masses appear to have had much the same area as they now have, the relief in Cambrian times may be assumed to have been of the same general order of magnitude as now. It may at least be assumed to have been sufficiently great to have involved these considerations. It will be seen that continental spreading or creeping will, within the limits of its operation, diminish the capacity of the ocean basins, and so tend to cause the waters to overflow the lands.

No attempt is here made to definitely estimate the efficiency of this agency, but some considerations which bear upon it may be cited: (1′) It cannot, probably, have been of a very high order, or it would have affected adversely the perpetuation of the continents to a greater degree than the record indicates. If the continental rock-masses spread with anything like the facility that continental ice-masses do, the land would probably have been completely submerged between each of the great periods of body deformation. It is believed that during great deformations the land segments are squeezed between the ocean segments, and forced up relatively (Vol. I, pp. 542–551), and that the perpetuation of the continents in the face of gradation, spreading, etc., is dependent on this periodic rejuvenation. As the periods between these rejuvenations of the continents appear to have been long, the lateral creeping action must have been slow and limited in amount relatively; yet it may have counted for something in the lowering of the surface, and in the spread of the sea. (2′) The *faulting* of the land areas is predominantly of the tensional type, and this type is hence called *normal.* Just how this type of faulting came to be a dominant one, is an outstanding problem of geology. It may have taken place in part during the periods of continental compression; but the thrust (reversed) faulting is most reasonably referred to these periods, and it is not easy to see how tension faulting could have predominated during a period of dominant lateral thrust. If tension faults did not occur abundantly during periods of compression, they are chiefly to be referred to the intervening periods of quiescence or relaxation, and the spreading of the continents would seem to furnish appropriate conditions. Normal faulting may therefore finally prove to be an evidence of a glacier-like, but extremely slow, creep of the continental masses. (3′) The upper portion of all formations composed of non-plastic rocks is affected by crevices, and these manifest a nearly universal tendency to gap. Taken altogether, the amount of gaping thus indicated is very considerable, even when allowance is made for enlargement by solution or any demonstrable shrinkage. Cracking and spreading of this kind is what might be expected if the deeper parts have crept laterally under pressure, just as similar cracks open and widen on the surface of asphalt when it slowly spreads under its own weight. Without affirming that this is the explanation of crevicing, or that it is evidence of continental spreading, the mutual fitness of the two is worthy of consideration.

(*b*) **Mutual adjustment of continental and oceanic segments.**—Continental spreading would be operative, as seen above, even if the base plane on which the continent may be conceived to rest were absolutely inflexible. This, however, is not the case, and there is need now to consider whether the continents might not sink and cause the ocean bottoms to rise by reciprocal action, like the two arms of a balance.

If the continental segments, taken as deep masses, weighed more than the equivalent portions of the sub-oceanic segments, they would have tended to settle down and force the latter up until they reached hydrostatic equilibrium. This would of course be opposed by the rigidity of the rock, as in the previous case. If the continental segments had a lower specific gravity than the oceanic segments, so that the two were in essential balance, there would have been no tendency of the former to sink, though the tendency to spread, as discussed above, would still remain.

Pendulum observations seem to show that, on the whole, the continental segments are now in approximate hydrostatic equilibrium with the oceanic segments, and on this is built the doctrine of isostasy, or the essentially balanced condition of the earth's crust, notwithstanding the inequalities of its height.[1] At the same time, pendulum observations seem to show that notably elevated regions, as for example that of the Cordilleran tract, stand higher than they would if they were in isostatic balance.[2] There is in such evidences, and in other considerations that cannot be stated with sufficient brevity for this place, ground for thinking that during profound bodily deformations the continental segments may be pressed up, in portions at least, beyond the plane of equilibrium, and that during the period of quiescence that follows, they tend to settle back to the equilibrium plane.

If this view be well taken, there is ground for believing that some portions of the Cambrian continents were pressed up beyond the plane of isostatic equilibrium during the late Proterozoic deformations, and that they slowly subsided during the long Cambrian period. In the nature of the case, such a movement would be unsymmetrically distributed, and the result would be manifested in slow, quiet warping. It would be more efficient in the early stages of the quiescent period than later, for erosion would join with the subsidence to relieve the overweighting.

(*c*) **Isostatic adjustments due to gradation.**—If the continent had been in isostatic equilibrium at the opening of the Cambrian period, the removal of matter from the protruding surfaces, and its deposition about the borders of the land, would have disturbed the balance and caused some tendency to warping; for even if the body of the earth be too rigid to be sensibly influenced by such changes, the local loading, where deep deposits were made, would somewhat compress the rock beneath, and the unloading, where the surface was cut away, would permit their expansion. Such effects would obviously be limited if the crust is inflexible to such moderate stresses; but the crust is sometimes held to be responsive to very moderate loading and unloading. The general result of changes of level brought about by this cause would, on the whole, be opposed to submergence of the land.

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[1] Dutton, Greater Problems of Physical Geology, Bull. Phil. Soc. Washington, XI; also Am. Jour. Sci., III, 1874; Woodward, Mathematical Theories of the Earth, Vice-Pres. Address, Math. Sect. Am. Assoc. Adv. Sci., 1899; also Smithsonian Rept. for 1890.

[2] Putnam and Gilbert, Bull. Phil. Soc. Washington, Vol. XII, pp. 31–75, and Gilbert, Jour. of Geol., Vol. III, p. 331.

(*d*) **Adjustments due to thermal changes resulting from gradation.**—The unequal erosion and deposition of the period tended to unequal loss of heat, and hence to unequal contraction, and so contributed slightly to superficial warping. The general effects of changes brought about in this way would have been opposed to those brought about by isostatic adjustments due to gradation.

(*e*) **Adjustments due to thermal changes incident to diastrophism.**—In the course of the distortion of the crust attending a great period of diastrophism, such as that which preceded the Cambrian period, unequal temperatures were undoubtedly developed in the compressed, contorted, and disrupted masses, and these tended to equalize themselves by distribution during the following period of quiescence, and this doubtless resulted in some gentle warping. This may have been a contributing cause to submergence.

(*f*) **Adjustments due to easing of stresses.**—So, too, in the process of distortion, unequal stresses must certainly have been developed, and these would tend to ease themselves by slow changes as time went on, and this also contributed to mild warpings and slight deformations. The general tendency of such changes was probably toward a lowering of the elevated segments of the earth.

Without attempting to make the list entirely exhaustive, it may be remarked that here is a group of changes which had their origin, for the greater part, *in previous diastrophism*, and which probably continued to slightly modify the configuration of the surface for a long time after the main diastrophic action had ceased. They may have coöperated with the gradational process through the Cambrian period. They may have interfered with the base-leveling process in some measure, and may have notably modified it locally; but, on the whole, because they aided in lowering the continents, they assisted in the general transgression of the sea, the great fact to be explained.

If these agencies are adequate, it is unnecessary to appeal to the more occult and periodic forces that affect the profounder deformations of the earth. More particularly is this true because, as already noted in passing, the usual effects of these profounder agencies are of the opposite character. Their normal work appears to be to deepen the ocean basins, to withdraw the epicontinental seas, to compress the continents laterally, and to increase their protuberances.

The general tenor of these considerations, taken in connection with the sedimentary record of the period, favors the view that from the beginning to the close of the Cambrian, there was general quiescence, so far as the profounder phases of bodily deformation were concerned, and that gradation (degradation of the land, and aggradation of the sea bottom) was a principal cause of the transgression of the sea, and that the transgression thus brought about was attended and modified by superficial warpings and deformations. These deformations were, for the most part, of the milder kind, and due to a series of minor readjustments springing largely from previous diastrophism, together with incidental causes of a superficial nature. Locally, they seem to have been somewhat pronounced, as indicated by the great local thicknesses of the Cambrian sediments, but as will be seen later (p. 257) the common interpretation of these great thicknesses may be called into question, at least to the extent of notably reducing the amount of deformations which they have been assumed to imply.

The base-leveling movement, attended by further sea-transgression, continued to be the dominant feature of the earlier portion of the next period.

Basis for the Subdivision of the Cambrian.

We have now to inquire the means by which the Cambrian strata may be recognized, and further the means by which the Lower Cambrian may be distinguished from the Middle, and the Middle from the Upper. In other words, how is it known that the strata shown in sections 18–26, of Fig. 96, are Cambrian, and how is it known that they are Upper Cambrian, as distinct from Lower and Middle.

Stratigraphic relations.—From what has gone before, it is evident that the stratigraphic relations of a formation with the formations next beneath do not necessarily determine its age. As the sections show, the Lower, the Middle, and the Upper Cambrian strata in turn rest unconformably upon pre-Cambrian rocks. Just as the Upper Cambrian overlaps the earlier formations of the period, resting unconformably on the pre-Cambrian, so any later formation might overlap the Upper Cambrian and sustain similar relations to the Proterozoic and Archean systems. It follows that where one formation is unconformable on another of known age, the stratigraphic relations between them do not determine the age of the younger, beyond the general fact that it is younger than the base on which it rests. If, on the other hand, a formation is conformable on another of known age, the presumption is strong that the upper succeeded the lower without interruption. If this inference be correct, the approximate age of the upper is known. But even here there is possibility of error. If, after a formation is deposited, the sea bottom where it lies is brought above water level without deformation of the beds, and if the elevation be so slight as not to permit of much subaërial erosion on the newly emerged surface, it might be submerged at a later time and receive a new series of deposits, the beds of which would be stratigraphically conformable, or approximately so, with those below. It is clear, therefore, that the answer to the question proposed in this paragraph is not always to be found in the stratigraphy of the formations concerned. The complete answer involves as well a consideration of the fossils which the formations contain.

Fossils.—It has been stated that life existed in the preceding eras. Yet in the Proterozoic formations, fossils are exceedingly rare, though it does not follow that life was sparse during their deposition. When, after the lapse of the long interval between the deposition of the youngest Proterozoic and the oldest Cambrian strata, as known in most parts of North America where detailed geological work has been done, the waters again advanced over the land surface, making the deposits which are now known as Cambrian, they teemed with life. As the sediments were deposited, the shells or such other hard parts as the animals possessed, were buried in the gathering sands and muds, and some of them, or the impressions which they made, remain to this day. The Cambrian is therefore the oldest known system of rocks which contains abundant fossils.

The fossils in the strata of any division of the Cambrian constitute the known fauna of that stage. The fossils found probably do not represent the full fauna of any stage, since it is hardly to be supposed that relics of all species have been preserved. The term fauna has both a geographic and a geologic significance. The Upper Cambrian fauna includes all forms of animal life of the Upper Cambrian epoch, while the Upper Cambrian fauna of New York includes only those forms which lived in that region at that time.

With the possible exception of the Atlantic coast region, notably Newfoundland, the oldest known part of the Cambrian system contains certain fossils which are distinctive. Among them are the species of a genus of trilobites known as *Olenellus* (Fig. 118 *a*, p. 281). Along with the representatives of the genus Olenellus, there are many other species of various types of life. To the aggregate, the name *Olenellus fauna*[1] has been given. It is not to be understood that representatives of the genus Olenellus itself are found at all points where the lower part of the Cambrian system is present, or that other genera of trilobites are absent. Wherever Olenelli are found, various species of other genera of trilobites occur, as well as various species of genera of other groups of animals, and wherever these other species of the Olenellus fauna are found, the Olenelli themselves may be expected. Geologists have very generally agreed to regard the base of the formations containing the Olenellus fauna as the base of the Cambrian system;[2] this definition of the base of the system has been found applicable both in America and Europe, and in both continents the Olenellus fauna is the oldest known abundant fauna. Conformable beds which lie below the Olenellus horizon, and whose character gives evidence that they were deposited immediately preceding the Olenellus beds and under the same general conditions, are better classed as Paleozoic than as Proterozoic, and they may be tentatively referred to the Cambrian.

As time went on, the inhabitants of the sea changed. Where the Cambrian formations represent a sufficiently long interval of time, the fossils in the lower beds are not altogether like those above. At no single plane is there, as a rule, a very notable change in species, but in successively higher beds some of the species found below disappear, and new species come in, as if to take their places.

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[1] For a general discussion of the Olenellus fauna, see Walcott, Tenth Ann. Rept. U. S. Geol. Surv.

[2] Walcott, Bull. 81, U. S. Geol. Surv.

Where the full system of the Cambrian is presented, the Olenellus fauna is found to be restricted to its lower portion. So strictly is this true, that (with the possible exception of Newfoundland, see p. 245) the rocks containing the Olenellus fauna are regarded as constituting the Lower Cambrian. *Olenellus Cambrian* therefore becomes synonomous with *Lower Cambrian* and with *Georgian.*

At about that stage in the Cambrian system where the genus Olenellus drops out, the genus *Paradoxides* appears; this is at least true for Newfoundland and Europe. The other species of fossils associated with the genus Paradoxides are somewhat different from those associated with the genus Olenellus, and many of them have a wider range than the Paradoxides. The Paradoxides and its associates constitute the *Paradoxides fauna,* a fauna which includes many species of other genera of trilobites, and many species of other classes of animals not related to trilobites. By general agreement, the Middle Cambrian of the regions specified is defined by the Paradoxides fauna, so that *Paradoxides Cambrian, Middle Cambrian,* and *Acadian* are synonomous terms. The Paradoxides fauna is so unlike the Olenellus fauna that the two may be distinguished by those familiar with fossils. In the western part of North America, the Middle Cambrian series does not contain fossils of the genus Paradoxides, but its fauna is none the less distinct from that of the Lower Cambrian series.

In like manner the Paradoxides (or other Middle Cambrian fauna) is succeeded by another, known as the *Olenus* or *Dikellocephalus fauna,* and this fauna characterizes the series of strata which overlie the Middle Cambrian. Geologists have agreed to define the Upper Cambrian as the series of strata carrying the Olenus or Dikellocephalus fauna. This definition is found to be applicable to Europe as well as to America.

It is not to be understood that every species of the Paradoxides or other Middle Cambrian fauna is unlike every species of the Olenellus fauna below and the Olenus fauna above. This is by no means true; but so many of the forms of the three faunas are different, that with a considerable number of species to judge from, their separation is possible.

In the discrimination of any of these faunas an analogy with living animals is suggested. The present faunas of North and South

America are reasonably distinct; but it does not follow that there are no species in common. Given a single animal, even an expert might not be able to say that it was from the one continent or from the other, though with certain species even this might be done; but if a large number of animals from either continent were available, it would be possible to determine to which continent, that is, to which *geographic fauna,* they belonged. So with the several Cambrian faunas. They have some species in common, and the common species do not serve to distinguish them, or the groups of strata which contain them, from one another. But certain species are found only in the Lower, certain other species only in the Middle, and still others only in the upper part of the system, and these species serve to distinguish the principal divisions. If but few fossils are present, and these not of decisive species, the several members of the system may not be separable one from another on paleontological grounds. Once the succession of faunas is established—Olenellus below, Paradoxides in the middle, and Dikellocephalus above—it is customary to refer all rocks which contain the Olenellus fauna to the Lower Cambrian, all which contain the Paradoxides fauna to the Middle Cambrian, and all which contain the Olenus or Dikellocephalus fauna to the Upper Cambrian.

Sequence of faunas based on stratigraphy.—It is not to be understood that rocks which contain such faunas are classed together simply because they contain certain fossils. This is not the principle, or at least not the only or the fundamental principle, which causes them to be grouped together. The order of sequence of faunas is first determined by the superposition of the strata. The Olenellus fauna could not be known to be older than the Paradoxides fauna, if the beds containing the former were not known to underlie beds containing the latter. It is likewise because of their superposition that the rocks containing the Upper Cambrian fauna are known to be younger than those containing the Middle Cambrian fauna; in other words, *the basis for correlation by means of fossils must necessarily be stratigraphic.*

Once the succession of faunas is established, the fossils become a most important aid in correlation, and frequently afford the only basis for it. It should be remembered, however, that the classing of rocks of different regions together under the name of Lower Cambrian means, not primarily that they contain the same fossils, but that they are believed to have been deposited at about the same time, and since the succession of faunas in different regions is believed to be in a general way the same, likeness of fossils in the formations of different regions is thought to be evidence of their approximate contemporaneity. Fossils, therefore, are but a means to an end, so far as the correlation of strata is concerned. It is not to be inferred, however, that the Olenellus fauna ceased to exist at exactly the same time in different regions of the same continent, much less in different continents, and the variations from a true chronological classification which the correlation by fossils involves cannot be avoided.

Upper limit of the Cambrian system.—Not only have the three principal faunal stages of the Cambrian been agreed upon, but it has been further agreed to draw the division line between the Cambrian system and that which overlies it at the horizon where the Olenus fauna ends. The upper limit of the Olenus fauna is therefore the upper limit of the Cambrian system, and corresponds in time with the end of the Cambrian period.

At first thought this division may seem arbitrary, but in reality it is not without a natural basis. The Upper Cambrian formations are occasionally unconformable beneath the next succeeding ones, and in such places the division is a natural one. Much more commonly, the next system is conformable with the Upper Cambrian; but even in conformable series, the faunal changes are more rapid in some parts than in others, and the horizon where the Olenus fauna ends is one where these changes are relatively abrupt. The horizons of rapid change in the character of the fossils may represent times of geographic changes, from which changes in sedimentation and life resulted. Throughout geological history great faunal changes have followed changes in the relations of land and sea.

Fig. 97 will help to make clear the principles here set forth. The vertical space of the diagram may be taken to represent the Cambrian system, and a part of the system next above. The fauna found at the bottom, *a*, undergoes gradual change in the overlying beds up to the horizon *b*. In the beds next following, *b* to *c*, the faunal changes are more rapid, and these beds represent the transition from the Lower to the Middle Cambrian. From *c* to *d* the Middle Cambrian fauna is found, though undergoing gradual change with successive beds. Between *d* and *e* the changes in the fossils are again more marked, and these beds represent the transition from the Middle Cambrian to the

Upper. From *e* to *f* the Upper Cambrian fauna is found. Between *f* and *g* the faunal changes are again more rapid and more profound than between *b* and *c*, or *d* and *e*. Since the changes at this horizon are greater than at the other corresponding horizons below, the faunas above and below *fg* are referred, not to different epochs of the same period, but to different periods. The beds between *f* and *g* therefore represent the transition from the Upper Cambrian to the next succeeding, or Ordovician fauna.

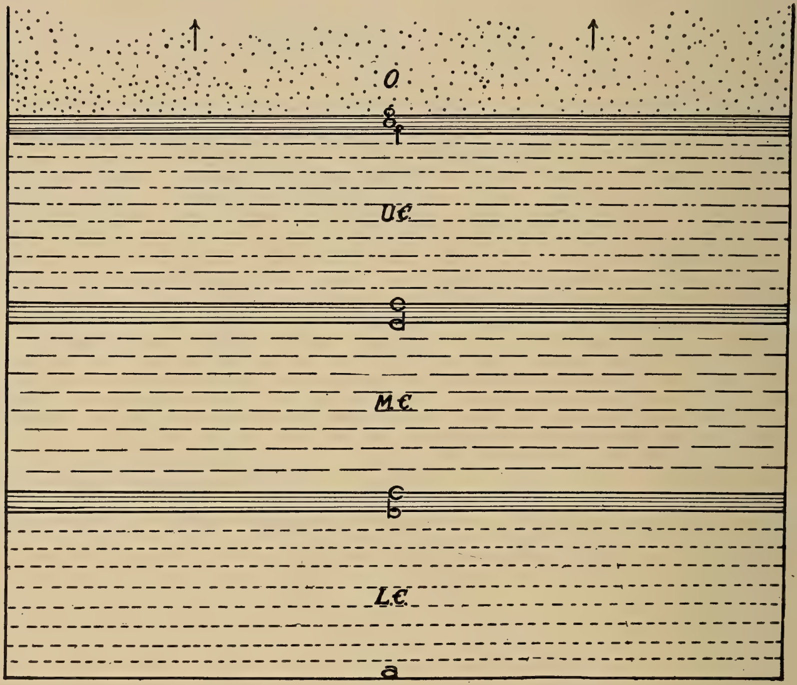

FIG. 97.—Diagram to illustrate classification based on unequally rapid transitions of faunas. The fossils of the strata, *bc*, *de*, and *fg* record more rapid changes of life than the strata *ab*, *cd*, and *ef*. *bc* represents the transition from Lower Cambrian to Middle Cambrian; *dc* from the Middle Cambrian to the Upper Cambrian, and *fg* from the Upper Cambrian to the Ordovician. *ab*, *cd*, and *ef* represent Lower, Middle, and Upper Cambrian respectively.

A few years since, question was raised concerning the accuracy and simplicity of the interpretation[1] of the Cambrian sketched above. One of the questions concerned the equivalence of the so-called Olenellus fauna of Newfoundland and Europe, and those of the Hudson-Champlain valley and the western part of North America. The Olenelli of Newfoundland and Europe were thought to be so different from the Olenelli of most of North America (see Fig. 118, p. 281) as to be more properly referred to another genus (Holmia), and the Holmia fauna, as a whole, was thought to be simpler than the Olenellus fauna, and therefore perhaps older. Furthermore, the distinct Paradoxides fauna is found only in those regions where the Holmia fauna occurs; it is not in immediate association with the commoner types of Olenellus. The stratigraphic relations of the types of Olenellus and Paradoxides faunas therefore is not established, *if the Holmia and Olenellus faunas be not one.* Question has also been raised as to the contemporaneity of the Middle Cambrian fauna of the larger part of North America, and the Paradoxides fauna of Europe.

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[1] Matthew, Am. Geol.. Vol XIX, 1897, p. 395.

In the Hudson-Champlain valley the Olenellus fauna appears to have lived on until the advent of the Dikellocephalus fauna. No well-marked Middle Cambrian fauna intervenes, though sedimentation seems to have been uninterrupted.

The questions which have been raised may lead to some minor modification of former views, but do not seem likely to change them fundamentally, or to lead to very different opinion concerning the course of the physical history of the continent in the Cambrian period. They seem to make two interpretations possible. The one is that the Holmia fauna of Europe and Newfoundland was contemporaneous with the Olenellus fauna of North America. According to this view, they are one geologically (chronologically), but somewhat distinct geographically. In this case it would not be strange that the succeeding faunas were also somewhat unlike, the Paradoxides fauna succeeding the Holmia in one region, and the Middle Cambrian, without the genus Paradoxides, succeeding the Olenellus fauna elsewhere. The geographic diversity may have been as great in the Middle as in the Early Cambrian. According to this view, the Olenellus fauna of the Hudson-Champlain valley may have been contemporaneous with both the Holmia and the Paradoxides fauna of the region farther east. A Holmia has been found in Pennsylvania, but a partial barrier between Newfoundland and the Hudson-Champlain valley, is supposed to have prevented free mingling of the contemporaneous Holmia and Olenellus faunas. It must be further supposed that the causes which brought about a change from the Early to the Middle Cambrian faunas, both to the east and to the west, did not produce like results in the Champlain valley, since the Lower Cambrian (Olenellus) fauna lived on. None of these assumptions are in violation of principles which are believed to have been in operation throughout geological history.

The alternative interpretation is that the Holmia fauna is really older than the Olenellus proper, and that the Olenellus of the west and of the Hudson-Champlain valley may have been contemporaneous with the Paradoxides of the east. According to this interpretation, the Paradoxides fauna of Newfoundland may have been contemporaneous, at least in part, with the Olenellus fauna of New York and with the Olenellus and Middle Cambrian faunas of the west. Like the last, this interpretation does not violate known principles of life development, for two distinct faunas in one region may have been contemporaneous with one fauna elsewhere, where the causes of biological change were notably less. Between these interpretations, the former now seems the more probable.

Sedimentation in the Cambrian Period.

Sedimentation in the Cambrian period appears to have followed the general laws that govern deposition in periods of comparative freedom from great deforming movements, and hence of progressive base-leveling. While at all stages there was doubtless some accumulation of sediment on land-areas and in land-waters, the chief sedimentation was in the sea, and the area of sedimentation may be regarded as corresponding approximately to the area of the sea. In general, the rate of sedimentation was probably faster in the early stages of the period when the land-area was largest and probably highest, and slower in the later stages after the land surface had been lowered by erosion, and narrowed by the encroachment of the sea. Geographically, the rate was probably more rapid near the land, and less rapid farther from the shores in deeper water, in accordance with general law; but possible exceptions to this are to be recognized at those stages when very extensive and shallow epicontinental seas had been developed by gradational processes, continental spreading, etc., for in such seas deposition far from shore perhaps kept close pace with that near shore, and may even in some cases have exceeded it.

Sources and kinds of sediments.—As in other geologic periods, the land-derived sediments came from the various formations then exposed to erosion, the larger part from those which were undergoing the most rapid degradation. The sediments gathered along the immediate borders of the land were generally different from those being deposited farther out at sea, but this difference was less marked as broad shallow epicontinental seas were developed, for in such seas the conditions were more nearly equal over wide areas. The deposits in the abysmal depths of the ocean were of course notably different from those of the terrigenous belt, but none of the former are known to be now exposed. Even along shore there were considerable variations, both because of variations in the character of the formations giving rise to the sediments, and because of the differences in wave, river, and current action.

The Cambrian formations include all common phases of sedimentary rocks. There are conglomerates, presumably accumulated near the shores of the time; there are sandstones, the sand of which was deposited in shallow water where the waves were sufficiently vigorous to keep the mud from settling; shales representing the deposits made in stiller or deeper water; and beds of limestone representing, for the most part, the accumulations of shells, etc., in regions to which terrigenous sediments were not carried in quantity. On the whole, the proportion of limestone is greater in the upper part of the system than in the lower, and toward the south and southeast, rather than in other regions.

Geographic variations in the sediments.—The distribution of these various sorts of sedimentary rocks, shows that various kinds of detrital beds were accumulating in different places at the same time, and at the same place at different times. Thus in the vicinity of Quebec, the Cambrian system is represented by 5000 to 6000 feet of shale. Between the Adirondack and the Green mountains there are 3000 to 5000 feet of shale overlying 1000 feet of limestone, and some of the limestone appears to be the time-equivalent of some of the shale of Quebec. In Washington County, N. Y., the Cambrian strata are 10,000 or 12,000 feet thick, the upper and greater portion being of slate (formerly shale) and sandstone, while the lower and thinner part (1400 feet) is limestone. Farther south, the system is composed chiefly of shale (or slate) and sandstone (or quartzite). In Tennessee and North Carolina there are great thicknesses of quartzite overlain by shales. In Georgia and Alabama, the thickness of the system is something like 10,000 feet, the strata being made up of shale and sandstone with some limestone.

In the southern part of the Appalachian region, the general order of deposition was sandstone, followed by shale, and that by a small amount of limestone. In Virginia, where the system is 3400 feet thick, it is chiefly made up of shale, which runs down well toward its base. North of Virginia, as far as New York and Vermont, there seems to have been a great variety of sediment, including many beds of limestone near the base of the system. Since throughout most of the Appalachian belt, all divisions of the Cambrian are represented, it is evident from the above statements that while limestone was forming in one region, sandstone and shale were forming in others, and *vice versa*. If the sequence of beds in the Appalachian region be compared with that in other regions, they are found to vary widely. Thus the Upper Cambrian of the interior is mainly sandstone, while that of the southern Appalachians is shale and limestone. Similar variations are encountered everywhere. They are indeed so prevalent that there is no sufficient reason for assuming that the Upper Cambrian of one region is represented by sandstone, because that is the formation of the corresponding time elsewhere.

Not only were beds of sediment of different sorts accumulated at the same time in different places, but they were accumulated at very different rates, as suggested by the sections in Fig. 96. It should be borne in mind persistently in the study of all stratified formations, that equal thicknesses of rock do not necessarily accumulate in equal periods of time. The full section of the Middle Cambrian, that is, all that was deposited during the whole of the Middle Cambrian epoch, seems to be present at many points, yet the thickness of the Middle Cambrian strata is far from uniform.

The Lower and Middle Cambrian sediments of the Appalachian belt appear to have been deposited in a narrow interior sea, or in bays, which lay between the pre-Cambrian rocks just east of the present mountains and the great interior land area to the west (Fig. 90). The beds accumulated in this narrow interior sea are such as to indicate that the water was shallow, in spite of the fact that the deposits are estimated to have a thickness of several thousand feet. This apparent contradiction may be the result of an exaggerated estimate of thickness, or, if the estimated thicknesses are correct, it may be explained by supposing that, as the sediments were laid down in the shallow water, the bed on which they gathered sank about as rapidly as they accumulated, so that the whole series, from bottom to top, was deposited in shallow water; or the beds may have been built out from the shore in sloping attitudes, their upper parts being always in shallow water. In the later part of the Cambrian period, the narrow Appalachian sea of the earlier epochs had become a part of the wider sea (Fig. 95) which covered much of North America, but the water remained shallow.

The Cambrian formations along the North Atlantic coast (New England and north) are such as to indicate that the sediments accumulated near shore and in shallow water, that during their accumulation there were frequent oscillations of level, but that, on the whole, the sea gradually gained on the land. The distribution of the formations in this region indicates that the deposits were made, in many cases, in narrow arms of the sea, surrounded, or nearly surrounded, by high lands composed of older formations. Limestone is, however, not altogether wanting (Fig. 98). The fossils of this region indicate that a land barrier existed to the east, in the region which is now covered with water, shutting off the region where the known strata accumulated from free connection with the open sea in this direction. They are also thought to indicate that the waters in which the sediments of this region accumulated were not in free communication with those in which the sediments of the Appalachian region were laid down.

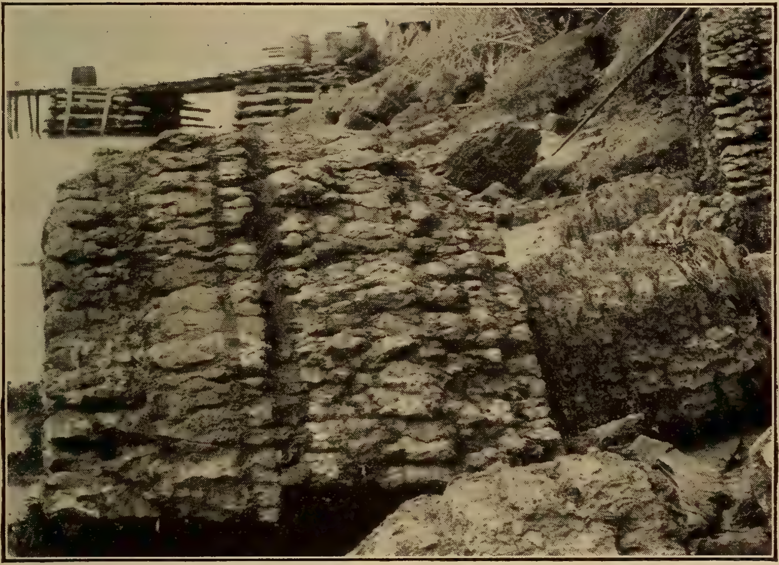

Fig. 98.—Nodular limestone, Lower Cambrian, from the east side of Smith Point, Smith Sound, Trinity Bay, Newfoundland. (Walcott, U. S. Geol. Surv.)

The fact that in the northern interior of the United States the Upper Cambrian formation is generally of sandstone, and that this sandstone is wide-spread, indicates that the water was so shallow during its deposition that the waves were competent to transport sand for long distances. Furthermore, the structure of the strata, with their cross-bedding (Fig. 99) and ripple marks, shows that the whole series, so far as seen, was deposited in shallow water, and therefore on a base which was gradually submerged as the sediments were accumulated.

In other words, the structure of the formation confirms the conclusion drawn from the distribution of the Upper Cambrian, that it was deposited in an advancing sea.

The greater portion of limestone, chiefly dolomite, in the Upper Cambrian series of the southern and southeastern interior, points to clearer seas, but not necessarily to deep ones. The adjacent lands were perhaps too low to yield abundant sediment. It has been conjectured, but not proved, that the limestone of the interior was largely precipitated from solution.[1] Limestone is also an important part of the Upper Cambrian of the Rocky Mountains,[2] though clastic rocks predominate farther west. Where the Upper Cambrian is limestone, it is not usually sharply differentiated from the overlying Ordovician. This is the case in the southern Appalachians,[3] as well as in Indian Territory, Missouri,[4] and Nevada.[5]

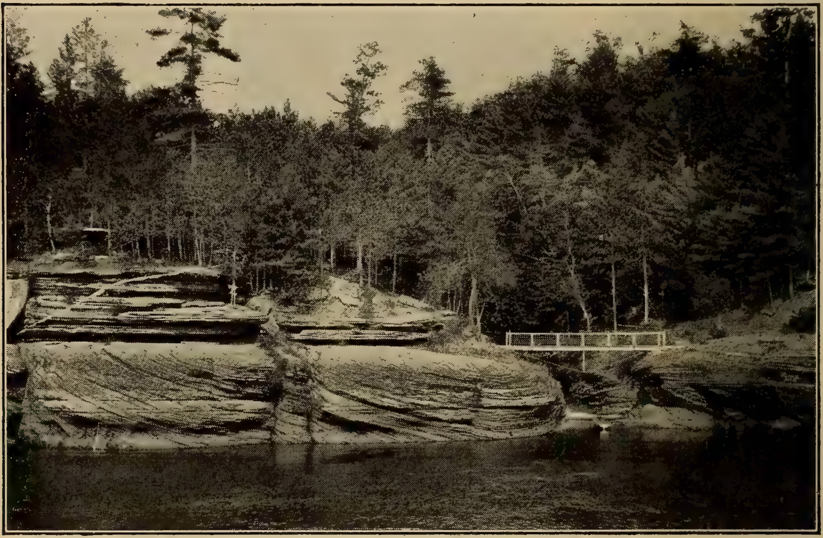

FIG. 99.—Cross-bedded Potsdam sandstone, Dells of the Wisconsin. (Blackwelder.)

Variation in a given locality.—The variations in the conditions of sedimentation in the same region are well illustrated by the sequence of beds in the Upper Cambrian of Wisconsin. In this state the formation had an original thickness of a thousand feet or so (less than this at its original margin), though within the area where it is now exposed its thickness is usually less. It is made up chiefly of sandstone, is indeed generally known as the Potsdam sandstone; but it is much less uniform from bottom to top than this name might suggest. The following section[1] represents the general sequence of beds in the south-central part of the State:

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[1] Ulrich and Schuchert, loc. cit., p. 637.
[2] Dawson, Bull. Geol. Soc. Am., Vol. XII, pp. 64–8.
[3] Folios U. S. Geol. Surv.; also Prosser, Jour. Geol., Vol. VIII, p. 662.
[4] Keyes, Am. Geol., Vol. XXIX, pp. 384–7.
[5] King, Geological Exploration of the Fortieth Parallel, Vol. I.

	Feet.
6. Sandstone (Madison)	35
5. Limestone, shale, and sandstone (Mendota)	60
4. Sandstone, calcareous	155
3. Bluish shale, calcareous	80
2. Sandstone, slightly calcareous	160
1. Very coarse sandstone, non-calcareous	280

The second division of the series from the bottom suggests either that conditions were such that shell-bearing life was rather more abundant than at first, or that the waters were more highly charged with lime carbonate. The third division, the bluish shale, shows that the sediments accumulating where this section occurs were finer than those which preceded or followed. This might mean either that the water was here temporarily deeper, or that the land from which the sediments were being derived was lower, so that finer sediment only was supplied. The fourth division represents a return to the conditions favorable for the accumulation of sand, while the fifth indicates that conditions had so changed that accumulations of sand alternated with those of mud and limestone. Toward the close of the period, there was a return to conditions favorable for the deposition of sand. Even this does not represent the full measure of the variations, for within each of the several subdivisions mentioned there are minor variations. These are often brought into prominence when the rock weathers (Fig. 100). Similar variations are repeated in many places for comparable thicknesses of rock, and each change in sedimentation probably indicates a change in the geography of the period.

[1] Geology of Wisconsin, Vol. I, p. 259.

Igneous Rocks.

At a few points igneous rocks are known to be associated with the stratified rocks of the Cambrian system. This is true in some parts of Newfoundland and Massachusetts. Igneous rock is also associated with some of the rocks thought to be Cambrian, lying west of the northern continuation of the Green mountains. Considerable thicknesses of igneous rock occur west of the Gold ranges in British Columbia.[1]

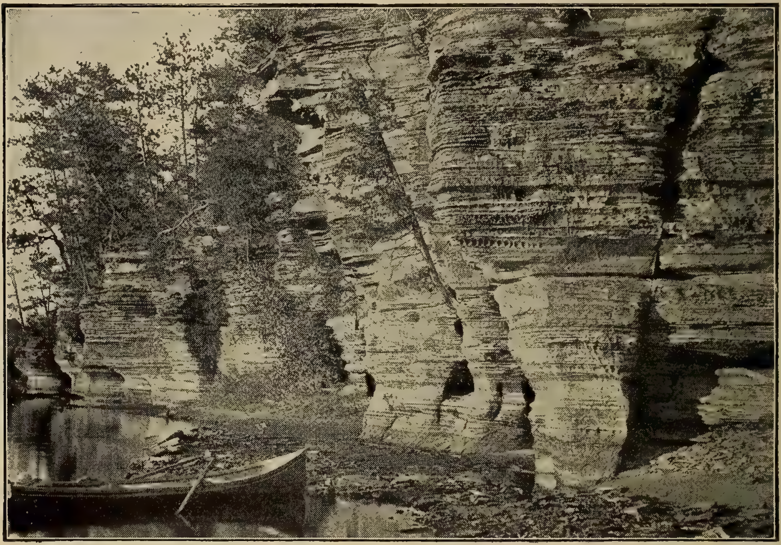

FIG. 100.—Figure showing inequalities of layers as shown by weathering. Potsdam sandstone, Dells of the Wisconsin. (Atwood.)

It is not always possible to tell whether igneous rocks associated with the Cambrian strata were erupted in the Cambrian period or at some later time.

Distribution, Thickness, and Outcrops of the Cambrian System.

The Cambrian formations were once as wide-spread as the Cambrian seas themselves, but it does not follow that they now exist over all the areas they once covered. Where exposed, the Cambrian rocks have suffered erosion, and the border of the system, as it now appears about the areas of pre-Cambrian rock, is not its original border, and does not represent the shore-line of the Cambrian sea when its waters were most wide-spread. Fig. 101 represents the conditions which often exist. Each of the Cambrian formations, represented by *A*, *B*, and *C*, formerly extended farther to the left.

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[1] Dawson, Bul. Geol. Soc. Am., Vol. XII, p. 85.

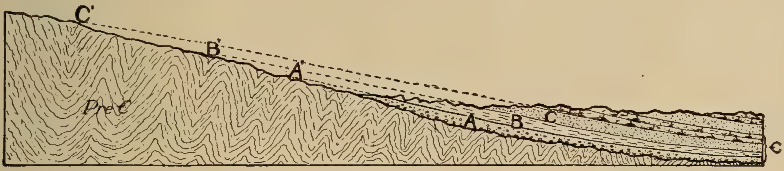

FIG. 101.—Diagram illustrating the relation of Cambrian formations, Ꞓ, to older rocks. The diagram suggests that the Cambrian formations have been eroded back from the original margins; thus *A* once extended to *A′*, *B* to *B′*, *C* to *C′*.

The areas where the Cambrian formations are exposed are not to be confounded with the areas where they actually exist. In Fig. 95 both these classes of areas within the area of North America are represented. The Cambrian formations are exposed, for example, in Wisconsin, in Missouri, and in Texas; but the strata of Texas are doubtless continuous beneath younger formations with those exposed in Missouri, and those of Missouri with those in Wisconsin, and these in turn with those of the Black Hills on the west, and with those of New York on the east. The diagrammatic section shown in Fig. 102 suggests the relations which are believed to exist. By far the larger part of the surface on which Cambrian formations were deposited was afterwards covered by younger formations. In so far as these overlying formations have not been removed, the Cambrian formations are still buried. This is doubtless true to a greater extent for the ocean bottom than for the continents.

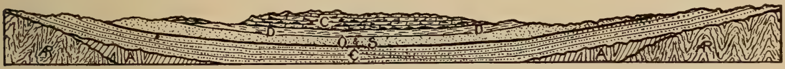

FIG. 102.—Diagram illustrating the general relations of Cambrian beds in the interior. The Cambrian, Ꞓ, is represented as appearing at the extremes of the diagram, and as dipping below younger beds between.

Position of outcrops.—The study of the maps (Figs. 90 and 95) showing the areas where the formations of the Cambrian system are now exposed reveals several points of significance. In the first place, the outcrops of the formation occur for the most part in association with the Archean and Proterozoic systems (compare Figs. 38 and 90). In some places, the exposed Cambrian borders the exposed parts of these older systems on one side only, while in others it completely surrounds them. Thus in the Black Hills of South Dakota, and in the Bighorn mountains of Wyoming and Montana (Fig. 94), the Cambrian formations, as now exposed, completely encircle areas of pre-Cambrian rock. In New York, Wisconsin, Texas, and British Columbia the Cambrian beds nearly encircle areas of older rocks, while in various other places, the Cambrian appears in linear belts along the sides of areas where the rock is of greater age. This distribution is not peculiar to the Cambrian, but is characteristic of most formations as compared with those of greater age.

The areas of Cambrian rock in the Appalachian mountains[1] are in contrast with the foregoing. Here the exposed Cambrian formations are not confined to the immediate borders of pre-Cambrian rocks, but occur in parallel or sub-parallel belts (Fig. 95). This is the result of (1) the folding to which the Cambrian and later strata of this region have been subject, and (2) the erosion which the folds have suffered. Fig. 103 will help to explain the repetition of outcrops. In this diagram, *A* represents pre-Cambrian strata, Ꞓ represents the Cambrian, and *O*, *S*, *D*, and *C* the Ordovician, Silurian, Devonian, and Carboniferous systems, respectively. After strata are folded, erosion may cut them down to any extent. The truncation of a fold below the level of the Cambrian leads to the exposure of two belts of that system, one on either side of a pre-Cambrian axis, as represented in the left-hand part of the figure. If the truncation was at a level below the top, and above the bottom of the Cambrian (right-hand side of Fig. 103), the strata of that system are exposed in a single belt along the crest of the fold. If parallel folds of unequal height occur, their truncation might give rise to two belts of surface Cambrian in some cases, and in others to but one, as illustrated by the figure.

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[1] For details concerning the Cambrian system of the Appalachians; see the following folios of the U. S. Geol. Surv.: Gadsden, Ala. (Hayes); Ringgold, Ga.–Tenn. (Hayes); Estilleville, Ky.–Va.–Tenn. (Campbell); Briceville, Tenn. (Keith); Chattanooga, Tenn. (Hayes); Cleveland, Tenn. (Hayes); Kingston, Tenn. (Hayes); Knoxville, Tenn.–N. C. (Keith); Maynardville, Tenn. (Keith); Morristown, Tenn. (Keith); Pikeville, Tenn. (Hayes); Bristol, Va.–Tenn. (Campbell); Harper's Ferry, Va.–Md.–W. Va. (Keith); Monterey, Va.–W. Va. (Darton); Pocahontas, Va.–W. Va. (Campbell); Staunton and Tazewell, Va.–W. Va. (Campbell).

In some other places, Cambrian outcrops are surrounded by older formations. This is the case, for example, in some places in the provinces of Mackenzie and Athabasca in Canada.[1] In such cases the Cambrian outcrops presumably represent remnants which have escaped erosion. Theoretically, they might occupy depressions in the surface of pre-Cambrian formations, or they might constitute hills (Fig. 104).

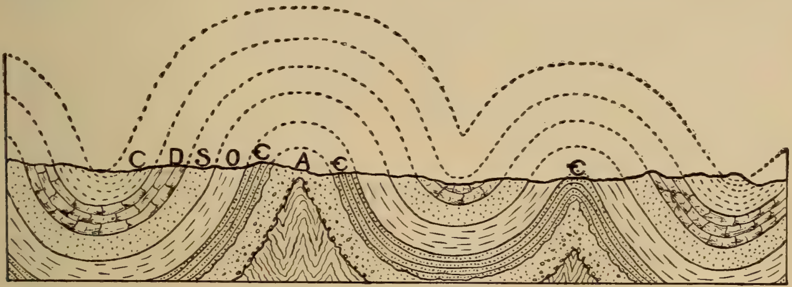

Fig. 103.—Diagram showing the positions of outcrops as determined by folds. The anticline at the right is represented as having been truncated in such a way as to expose the Cambrian, Є, in a single belt. The anticline to the left has been cut so as to expose pre-Cambrian formations, *A*, beneath, and the Cambrian, Є, outcrops in two belts, one on either side of the older formation.

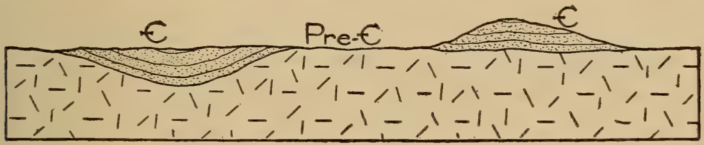

Fig. 104.—Figure to illustrate the occurrence of Cambrian in isolated areas surrounded by older formations. The diagram illustrates two ways in which such isolated areas may occur.

Again, more or less circular areas of exposed Cambrian are locally surrounded by the outcrops of younger formations, as at some points west of Hudson bay. An explanation of such areas is suggested by Fig. 105.

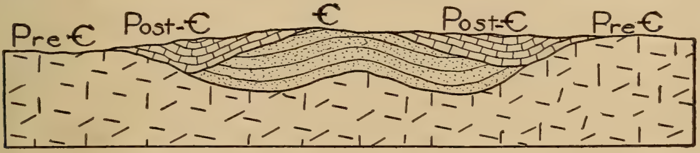

Fig. 105.—Diagram illustrating how an isolated area of Cambrian may be surrounded or bordered by younger formations.

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[1] Geological map of the Dominion of Canada, Western sheet, edition of 1901

Width of outcrops.—Certain other principles of geological cartography are illustrated by the outcrops of the Cambrian system. The most extensive continuous outcrops (Fig. 95) are in Wisconsin, and yet in that State the Upper Cambrian only, with a thickness of less than 1000 feet (see Fig. 96) is present, while in the Appalachian mountains, where the Upper, Middle, and Lower Cambrian are all present, with an aggregate thickness of several thousand feet, the system appears at the surface in narrow belts only. That is, the outcrops are narrow in the east where the system is thick, and wide in the interior where it is thin. From Fig. 95 it is also seen that in various parts of Nevada, Utah, Montana, and British Columbia, where the system is many times as thick as in Wisconsin, the outcrops of the system are much narrower.

The explanation of this apparent anomaly is to be found primarily in the attitude of the strata. In Wisconsin they are nearly horizontal, while in the mountain regions, both east and west, they are tilted, often at high angles. Where the strata are vertical or nearly so, the width of their outcrop on a horizontal surface is about the same as the thickness of the beds, as shown in Fig. 103 and the right-hand side of Fig. 106. Where they are nearly horizontal, as in the left-hand side of Fig. 106 the width of the outcrop is much greater. Thus in the Appalachian mountains, where the thickness of the strata is locally as much as two miles, their high inclination reduces their outcrop to a narrow belt, while the corresponding strata in Wisconsin, less than 1000 feet thick, but nearly horizontal, have a much wider outcrop.

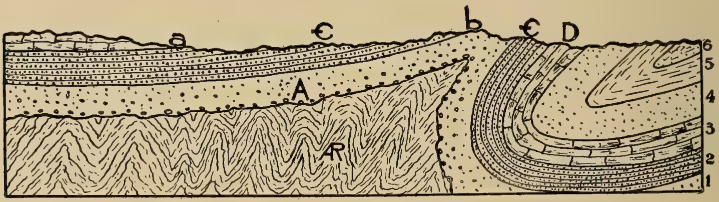

Fig. 106.—Diagram illustrating the influence of dip on the width of outcrop. The Cambrian beds, Ꞓ, to the left have a much wider outcrop than the Cambrian beds to the right, though the thickness is the same.

It is not to be inferred, however, that horizontal strata necessarily determine a wide outcrop. The width of the outcrop is also influenced by topography, as shown in Fig. 107. Here the horizontal stratum between *B* and *C* has about the same thickness as *C* of Fig. 106, but a much narrower outcrop. In general, the width of outcrop for a formation of given thickness, so far as determined by topography, depends on the angle between the bedding-planes and the surface where the formation outcrops. The width of the outcrop decreases as this angle increases.

In an area such as Wisconsin, it is not to be supposed that the edge of the Cambrian, as it laps up on older formations, represents the most advanced shore-line of the Cambrian sea. The sea doubtless extended farther up on the older land, depositing sands and other sediments on its surface; but in the long periods of erosion which have ensued, the edge of the formation as originally deposited has been destroyed (Fig. 101). Except in those cases where strata are absolutely vertical or horizontal (and few strata occupy either of these positions), the lowering of the surface by erosion must always shift the position of the outcrop of any formation, and almost always in its direction of dip.

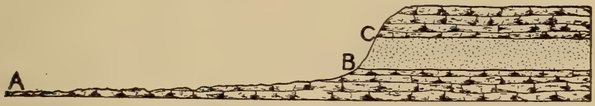

Fig. 107.—Diagram illustrating the effect of topography on the width of the outcrop.

Thickness.—Reference has already been made to the thickness of the Cambrian system in some parts of the continent, and the relative thickness in different portions of the continent is graphically represented by the sections of Fig. 96. These sections show the thickness to be great in the mountain regions of both the east and west. In the former region, the system attains a maximum known thickness of about 12,000 feet (more than two miles), and in the latter of something like 40,000 feet[1] (west of the Gold ranges in British Columbia), while over the interior it rarely exceeds 1000 feet. The greater thicknesses were probably accumulated near the shores of relatively high lands, where the supply of sediment was great.

Infirm Deductions from Thickness.

The literature of geology is by no means free from infirm deductions based on the reputed thicknesses of sediments. For example, when 40,000 feet of beds are assigned to the Cambrian section west of the

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[1] Dawson, Bull. Geol. Soc. Am., Vol. XII, pp. 62 and 64–8.

Gold range, or 50,000 feet to the Keweenawan, and when these systems show signs of deposition in comparatively shallow water, it is commonly inferred that the bottom of the basin of deposition sank during the deposition to an amount corresponding approximately to these great thicknesses. Now these are depths much greater than the deepest parts of the oceans. Moreover, they are depths where high temperatures should be experienced,[1] and where the pressure should exceed the elastic limit of all known rock (estimated at about 30,000 feet),[2] and all crevices and pores should be obliterated and the rock particles pressed into complete continuity, and highly metamorphosed. In the face of these rather startling inferences, two attitudes have developed. On the one hand, the correctness of the measurements or estimates of these great thicknesses has been questioned, as the basal parts of the thick series do not show these effects. On the other hand, accepting the measurements, in the main, far-reaching theories relative to crustal deformations and internal dynamics have been built upon the supposed deep depression of the surface. It is therefore important to inquire whether the fundamental assumption involved is correct, viz., that the thickness of a series of beds deposited in a body of water is a true measure of the depth of the basin receiving the deposits, or of the amount of its depression while receiving them.

One phase of the case may be clearly seen by consulting Fig. 108, in which the usual conditions for the deposition of sediments on the border of a continent are represented. When the sea covers the continental shelf, deposition takes place both on it and on the slope to the abysmal depths of the ocean, and very slightly on the deep bottom of the ocean. When the sea is withdrawn from the surface of the continent, the shore stands near the upper edge of the abysmal slope. That this has recently been the case is shown by river-channels that extend across the upper surface of the present continental shelf, and have their termini on the upper border of the abysmal slope. The main deposition is then on the slope, while slight deposition continued on the abysmal bottom. As deposition on these abysmal slopes has gone on throughout the whole history of the ocean basins, very extensive series of beds have been laid down. Because of the different attitude of the sea to the slope, the deposits have doubtless varied much in character. They were doubtless laid down fastest, and were coarsest, when the shore stood on the slope, as it has recently done, and as it probably has usually done after periods of body deformation when the seas were withdrawn more fully than usual within the oceanic basins, and when the continents were hence more protuberant and gradation more active. On the other hand, when the thin edge of the sea lapped over the border of the continent, the deposition on the abysmal slope was doubtless slower and the deposits were composed of finer material, forming shale or limestone. These details are merely to emphasize the persistent nature of the deposition on the abysmal slopes, and its varied character. The upper portion of the deposit on the abysmal slopes took place normally in rather shallow water, and from its exposed position this upper portion must always have been especially subject to the action of ocean currents and tidal waves which tended to give it the characteristics of agitated water-deposits, which we usually interpret as shallow water deposits.

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[1] See Dana's Manual, pp. 451 and 469.

[2] Van Hise and Hoskins, 16th Ann. Rept. U. S. Geol. Surv., also this work, Vol. I pp. 218, 219.

The abysmal slope usually dips from 2° to 5° and hence these are about the deposition angles of the beds laid down on it. Now when these beds have become accessible by deformation and truncated by erosion, they are measured along the surface, which may be represented by the line *EF*, Fig. 108. There are two common modes of measurement: (1) The beds are measured individually, or by groups, at right angles to the bedding-planes, and the sum of the whole ascertained; or (2)

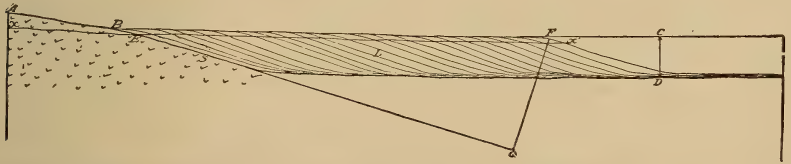

FIG. 108.—Diagram of a series of beds formed on the abysmal slope of a continent, or in similar situations, showing that the thickness as usually measured is not dependent on the depth of the basin, and that a thick series does not necessarily imply subsidence, even when the exposed portions of it show evidences of shallow-water deposition at various horizons. *A*, border of the continent, or rim of the basin; *B*, border of the depositional area; *C*, ocean-level; *D*, ocean-bottom previous to deposition; *S*, slope of abysmal basin at the beginning of deposition; *EF*, surface developed by erosion after emergence; *L*, beds deposited in sloping attitude; *EFG*, triangle by which the thickness of the series is measured; *FG*, computed thickness of beds. When compared with *CD*, the depth of the basin, a marked difference will be seen, and it will be obvious that the difference will vary with the length of *EF*.

the average dip of the beds is taken and the distance across the truncated edges, *EF*, is measured and the thickness of the whole computed by trigonometry. The angle at *G* being a right angle, the angle *FEG* and the side *EF* being known, the length of *FG* is readily ascertained, and this is the thickness of the series, as usually measured when the thickness is great. By comparing the line *GF*, representing the thickness of the series, with the line *CD*, the depth of the ocean, a marked difference will be seen. Moreover, consideration will show that the difference may vary indefinitely, and that there is no necessary relation between the two. If the line *EF* be short, as it would be if the series had not been built far out, the thickness *FG* would be less than the depth of the ocean, *CD*; but if the line *EF* be long, as it would be if deposition were continued sufficiently, the thickness of the series, *FG*, would be proportionately increased, while *CD* might remain constant. In other words, *the thickness of the series may vary from any fraction of the depth of the basin to any multiple of it*, within certain limits imposed by the width of the basin.

Similar considerations reveal a discrepancy between the vertical measurement and the thickness of the beds deposited subaërially. For example, the thickness of the beds of a typical volcanic cone is *less than the height of the cone which they form*, as will be seen from Fig. 109. Lava-flows poured forth on heights, and congealing as they spread out upon the slopes below, may give rise to series of great aggregate thickness, without implying any contemporaneous sinking or other crustal change. Clastic beds formed by slope-wash may become interleaved between these lava-flows without implying subsidence. In this case, the *horizon of wash is shifted* to higher and higher positions in the series (not necessarily to higher altitudes), but the *series of beds is not lowered.* In the case of the Keweenawan system, a congelation or deposition slope of 5°, extended horizontally a little over one hundred miles, or about half across the Keweenawan basin, as it may have been before compression, would give the estimated thickness (see p. 192). To explain the present attitude, it is necessary to suppose that the series was compressed laterally, so that the beds were upturned and somewhat sheared upon one another (Fig. 110). A greater upturning must of course be supposed, if the alternative view is taken that the beds were originally strictly horizontal.

It is not here affirmed that this is the explanation of the great apparent thickness of the Keweenawan series, certainly not that it is the whole explanation, though it seems to throw important light on it. The point here made is merely that great apparent thickness may and does arise in this way, and that inferences and doctrines that overlook this fact have an insecure basis.

In the case of such sedimentary beds as are formed on mountain slopes, the sides of intermontane valleys, or in other situations where there is an appreciable deposition angle, the thickness of the beds varies indefinitely in comparison with the vertical range of the deposit.

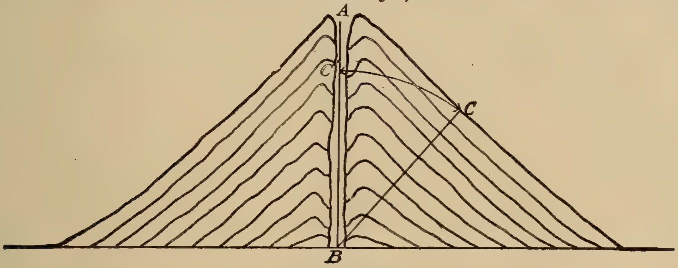

Fig. 109.

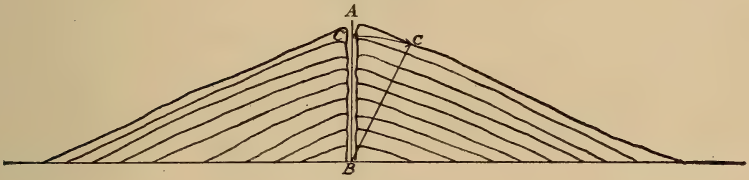

Fig. 109*a*.

Figs. 109 and 109*a*.—Diagrammatic illustration of relation of thickness of beds to height of accumulation in the case of volcanic cones. *AB*, height of cone; *CB*, aggregate thickness of layers, which is obviously less than *AB*.

Delta deposits furnish especially good illustrations of the point under discussion, and delta deposits have probably been elements in the deposits of all the great periods, though not always readily recognizable in their buried condition. If the Amazon were to build out a delta 200 miles, the ocean bottom remaining absolutely immovable at an average depth of four miles below the surface, and the deposition angle were to be on the average 2°, the computed thickness of the series, according to current methods of measurement, would be about seven miles. If the delta were built out 1000 miles, the computed depth would be thirty-five miles. In a lake 100 miles wide and 1000 feet deep, in which the deposition angle was 3° on the average, and in which the filling grew outward from each shore fifty miles, meeting in the center, the thickness of the series on each side, measured by the above standard method, would be 13,800 feet, no change at all in the bottom or the surface of the lake being assumed. If the Nile should fill up the eastern end of the Mediterranean, the Danube the Black sea, and the Mississippi the Gulf of Mexico, with no essential change in the bottoms of the basins or the surfaces of the water-bodies, series of beds of prodigious thicknesses, as thicknesses are commonly estimated, would be the result. The usual changes in the sea-bottoms, changes of both upward and downward phase, might take place during the process of filling, without seriously affecting the result.

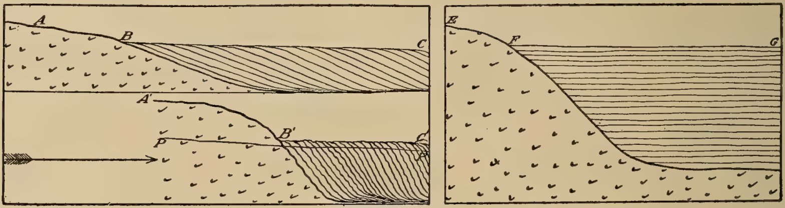

Fig. 110.—Diagrammatic section illustrating the assigned change of attitude of a series of beds, like the Keweenawan, from an original depositional inclination, to a more highly inclined attitude, a comparatively simple change. If the beds were laid down horizontally in a sinking basin, as illustrated at the right, it is obvious that a greater and a more complicated movement would be necessary to bring the beds into the attitude represented in the lower figure at the left, which represents the present attitude of the Keweenawan beds.

Dwelling on these aspects of the case, we almost reach the conclusion that the thickness of a series of beds, *as we usually measure thicknesses where they are great,* is independent of the depth of the basin. This, however, is pushing the case too far, for the considerations that have been urged apply only to deposition of the kinds specified, i.e., *deposition on appreciable slopes.* When deposition takes place by strict superposition in horizontal attitudes, the usual inference of a correspondence between the depth of the basin, or the sinking of its bottom, and the thickness of the series, holds good. Moreover, when the beds above and below are accessible, or penetrable by borings such as wells, over large areas, the vertical depth of deposition may be conclusively ascertained. This is usually the case with the deposits of the broad shallow epicontinental seas. In them, oblique deposition is usually a minor phenomenon. But the deposits of the shallow epicontinental seas, laid down on plane surfaces, should not be confused with the deposits built out on the border slopes of the deep basins.

Applying these considerations to the varying thicknesses of the Cambrian beds, it is to be observed that any deep portion of the seas, not simply the ocean border, which was filled from the side by a gradual building out on the slopes, was liable to develop a thickness of beds disproportional to the depth of the water. At the same time, the superposition of great sheets of sediments covering broad epicontinental areas, as those of the interior in late Cambrian time, was probably rendered possible only by a change in the relation between the sea-bottom and the sea-surface. This change probably consisted in part in a raising of the sea-surface by sea-filling, and in part in the sinking of the surface on which the sediments were deposited.

The apportionment of the relative influence of these several factors in the development of the observed thicknesses of rock is a difficult matter, requiring a careful study of all available sources of evidence to be found in the character of the deposits, in their relations to overlying and underlying formations, and in the topography of the Cambrian sea-bottom, so far as it can be reconstructed. Unless the interpretation can be made with great assurance of correctness, inferences as to crustal movements based simply on the thicknesses of deposits may well be entertained with reserve, and doctrines based on extreme subsidence inferred from these thicknesses may well be regarded as lacking a firm basis.

Selected Sections.

The following sections of the Cambrian, at widely separated points, give some idea of the range of the system both as to thickness and kinds of rock, and therefore of the variations in the conditions and in the rate of sedimentation.

SECTION IN SOUTHEASTERN NEWFOUNDLAND.[1]

	Thickness in Feet.	Characteristics.
Middle and Upper Cambrian.	476	Brown and black micaceous shales, with gray micaceous sandstones; Bell island, Concepcion bay.
	1426	Red and green sandstones and slates, with calcareous beds at the base.
	720	Kelly's Island sandstones and shales, containing a few fucoids.
	150	Black slate or shale; Middle Cambrian fossils.
	5	Dark-gray limestone.
	1045	Red, green, and black slates or shales; Middle Cambrian fossils.

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[1] Walcott (section after Murray), Bull. 81, U. S. Geol. Surv., pp. 257–8.

SECTION IN SOUTHEASTERN NEWFOUNDLAND.—*Continued.*

	Thickness in Feet.	Characteristics.
Lower Cambrian.	100	Hard thick beds of gray, and sometimes reddish limestone; Lower Cambrian fossils.
	250	Red, green, and blackish argillaceous slates.
	50	Conglomerate of Manuel's brook, not recognized elsewhere.
	150	Red and green argillaceous shales or slates.
	20	Red and flesh-colored limestone; obscure fossils.
	30	Red slate.
	10	Impure limestone.
	40	Red slate.
	750	Red, green, and gray sandstones, with occasional beds of conglomerate; upper beds flaggy.
	137	Green and reddish-brown or purple slates.
	3	Impure flesh-colored limestone.
	10	Green slate.
	600	Hard, dark, green-gray thin-bedded sandstones with slaty divisions.
	Unconformity. Proterozoic and Archean.	

Strata dip at low angles.

SECTION IN WESTERN VERMONT.[1]

	Names of Formations.	Thickness in Feet.	Characteristics.
Upper and Middle Cambrian.			Cut off by a fault above.
		3500 to 4500	Arenaceous shales.
		1700	Massive gray limestone, with intercalated bands of hard argillaceous shale.
		50	Light-gray quartzite.
		3500	Argillaceous shales; occasional thin layers of hard gray limestone; numerous fragments of a linguloid shell.
Lower Cambrian.	Georgian shales.	200	Argillaceous, micaceous, and arenaceous shales; numerous Lower Cambrian fossils.
		190	Gray arenaceous limestone in rough, massive layers, passing into more evenly bedded, light-gray arenaceous limestone; fossiliferous.
	Red Sandrock series........	100	Reddish-pink dolomitic limestone; fossiliferous.
		475	Massive gray dolomitic limestone.
		200	Steel-gray dolomitic limestone with bands of mottled limestone; some reddish dolomite.
		35	Massive bluish gray dolomitic limestone, with threads and bunches of yellowish-drab sandy limestone that weathers in relief.
	Base unknown.		

Strata dip at high angles.

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[1] Walcott, Bull. 81, U. S. Geol. Surv., pp. 277–280.

SECTION IN MASSACHUSETTS.[1]

	Names of Formations.	Thickness in Feet.	Characteristics.
Middle Cambrian.	Braintree section. .	1000 –	Conglomerate of quartzite pebbles and sandstone.
		500 to 1000	Greenish-gray, fine-grained, siliceous slates; Middle Cambrain fossils.
	Discontinuity.		
Lower Cambrian.	North Attleboro (belongs below Braintree section).	2000 ±	Thin-bedded shales which occasionally pass into fine-grained greenish and reddish slates; a few beds of conglomerate varying from 200 to 300 feet in thickness; some beds contain Lower Cambrian fossils; little metamorphosed.
	Unconformity. Archean.		

Strata dip at high angles.

SECTION IN NORTHERN NEW JERSEY.[2]

	Names of Formations.	Thickness in Feet.	Characteristics.
	Trenton formation. Unconformity.		
Upper and Middle Cambrian.	Upper part = Lower Ordovician. Kittatinny limestone. (Lower part = Lower Cambrian.)	2700 to 3000	Blue or gray, sometimes nearly black limestone, variable in texture, composition, and color; arenaceous at base.
Lower Cambrian.	Hardiston quartzite...	0 to 185	Sandstone, quartzite, locally arkose; intercalated beds of shale and dolomitic limestone; Lower Cambrian fossils.
	Unconformity. Pre-Cambrian.		

Strata gently folded.

The published sections of the Cambrian of Texas are not altogether in accord.[3] The Middle and Upper Cambrian series are represented by sandstone and limestone. The Lower Cambrian also is thought by Comstock[1] to be present. It is possible that the Lower Cambrian is present at some points and not at others. The Cambrian is unconformable on its base, and according to Comstock[1] there is also unconformity between the three main subdivisions of the Cambrian. The thickness varies from point to point, the published sections giving 600 to 1000 feet or more. Strata nearly horizontal.

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[1] *Ibid.*, pp. 268–73; and 10th Ann. Rept. U. S. Geol. Surv., p. 567.

[2] Kümmel and Weller, Bull. Geol. Soc. Am., Vol. XII, pp. 147–154.

[3] Walcott, Bull. Geol. Soc. Am., Vol. X, p. 218; 10th Ann. Rept. U. S. Geol. Surv., p. 552; Bull. 81, U. S. Geol. Surv.; and Am. Jour. Sci., Vol. 28 (1884), pp. 431–33; and Comstock, First Ann. Rept., Geol. Surv. of Texas, 1889, pp. 285–292.

In west central Colorado[2] (Tenmile region) 160 to 200 feet of white quartzite, more or less argillaceous above, represents the Cambrian system. The formation carries Upper Cambrian fossils, and rests on the Archean unconformably. Strata gently folded.

In north-central Utah[3] (Tintic region) the Cambrian is represented by the Tintic quartzite, which has a thickness of some 7000 feet. Since this quartzite is not known to carry fossils, and since it is conformably overlain by Carboniferous formations, it may not all be Cambrian. Strata much folded.

In the Wasatch Mountains[4] the Cambrian rests conformably on the Proterozoic. The Lower Cambrian is represented by slate 75 to 600 feet thick. This slate is overlain by the thick Ute limestone, 1000 to 2000 feet thick. The lower shaly part only of this formation contains a Middle Cambrian fauna, and the Upper Cambrian fauna is not known. The larger part of the Ute limestone is Ordovician, and its top may be Silurian. Strata much folded and faulted.

In the Rocky mountains of Canada the following Cambrian section[5] occurs.

Names of series.	Thickness in feet.	Characteristics.
Castle Mountain series.	8,000	Consists of limestone, dolomites, shales, slates, and schists. The lower part carries Lower Cambrian fossils, and the uppermost part fossils which appear to be Ordovician.
Bow River series.	10,000	Chiefly argillites with some sandstone, quartzite, and conglomerate. Lower Cambrian fossils occur 3000 feet below the top.

Summary of physical events and interpretations. — The accumulation of a thick series of beds in certain regions and the spreading of a relatively thin sheet over a large part of the American continent are matters of positive determination. The immediate agency by which this was accomplished is found in the wear of the land and the deposit of the débris in the adjacent seas. The remoter agencies that furnished the conditions under which the erosion and the deposition took place are less certain, and have been assigned to different sources by different investigators. The preponderant tendency has been to give a leading place to crustal movement. On the other hand, in the previous discussion a preference has been indicated for assigning the leading place to gradation, and for attributing such deformations as obviously took place to superficial causes that were largely inherited from the Proterozoic or post-Proterozoic diastrophism. On this view, the period was one of general quiescence and almost free from profound deformation. This interpretation makes the Cambrian a period of progressive base-leveling, modified in some degree by superficial deformations. The gradational interpretation has the merit of accommodating automatically, as it were, the erosion that furnished the material, to the planation that provided the nearly level expanse on which the broad sheet of the later Cambrian was spread.

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[1] See foot-note, p. 221.

[2] Emmons, Ten Mile (Colo.) folio, U. S. Geol. Surv.

[3] Emmons, Tower, and Smith, Tintic (Utah) special folio, U. S. Geol. Surv.

[4] King, Expl. of the 40th Parallel, Vol. I, p. 156; Walcott, Bull. 81, U. S. Geol Surv., pp. 157–60. and p. 328.

[5] McConnell, Ann. Rept. Geol. Surv. of Canada, Vol. II (New Series), Pt. D

Changes in the Cambrian sediments since their deposition.—Since their deposition, the sediments of the Cambrian system have undergone more or less change. In most regions the gravels, sands, and muds have been compacted and cemented into conglomerates and sandstones and shales respectively. In some places the cementation of the sandstone has been carried so far as to convert it into quartzite, though this is not the rule. Over great areas in the interior (Missouri, Wisconsin, Texas, etc.) the strata still remain in horizontal or nearly horizontal position (Figs. 102 and 107), while in other regions they have been tilted and even folded. Where close folding has taken place, the

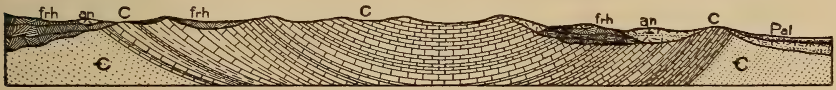

FIG. 111.—A section showing the relations of the Cambrian at one point (near Tintic) in Utah. **Є**, Cambrian; *C*, Carboniferous; *frh*, rhyolite; *an*, andesite; *Pal*, Pleistocene formations. Length of the section, about 6 miles. (Emmons, Tintic (Utah) folio, U. S. Geol. Surv.)

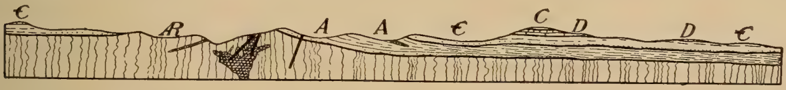

FIG. 112.—Section showing relations of the Cambrian at a point in Montana. *Æ*, Archean; *A*, Proterozoic; **Є**, Cambrian; *C*, Carboniferous; *D*, Devonian. Length of section, about 20 miles. (Weed, Little Belt (Mont.) folio, U. S. Geol. Surv.)

dynamic action involved has had a metamorphosing effect on the rocks. Thus in the mountains of the eastern part of the United States the original sandstones have been converted into quartz schists, the shales into slates and schists, and the limestones into marble where the dynamic movements were profound, and less altered where the folding was simple. Fig. 102 shows the general position of the Cambrian strata (€) over much of the interior. Fig. 111 shows their position and relations in the vicinity of Tintic, Utah; Fig. 112, at a point in Montana;

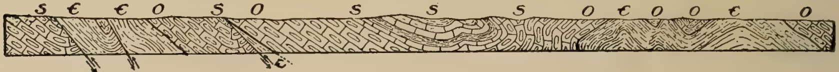

Fig. 113.—Section showing the relation of the Cambrian in the Appalachian mountains. The strata are both folded and faulted. *€*. Cambrian; *O*, Ordovician; *S*, Silurian. Length of section, 13 miles. (Hayes, Cleveland, Tenn. folio, U. S. Geol. Surv. Ordovician and Silurian not separated in original.)

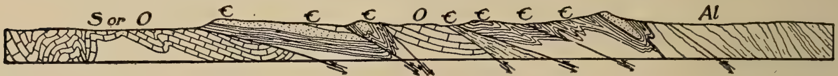

Fig. 114.—Section showing the relations of the Cambrian at another point in the Appalachian region where the faulting has been extreme. *Al*, Proterozoic; *€*, Cambrian; *O*, Ordovician; *S*, Silurian. Length of section, about 8½ miles. (Keith, Harper's Ferry, Va.-Md.-W. Va. folio, U. S. Geol. Surv. Ordovician and Silurian combined in original.)

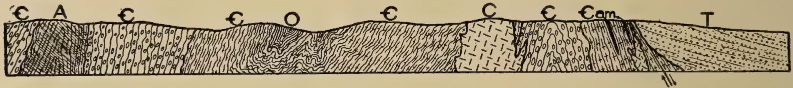

Fig. 115.—Section showing the relations of the Cambrian at a point in Massachusetts where the rocks are much metamorphosed. *A*, Proterozoic; *€*, Cambrian; *O*, Ordovician; *C*, Carboniferous; *T*, Triassic; *am*, amphibolite. Length of section, about 11¼ miles. (Emerson, Holyoke, Mass. folio, U. S. Geol. Surv.)

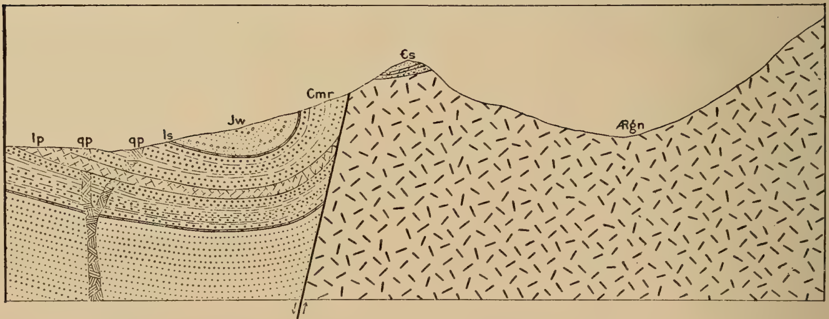

Fig. 115*a*.—Section showing the relations of Cambrian and other formations at a point in Colorado a little north of Leadville. *Ægn*, Archean; *€s*, Cambrian (Sawatch quartzite); *Cmr*, Carboniferous (Maroon formation); *Jw*, Jurassic (Wyoming formation); *lp* and *qp*, igneous rocks. (Emmons, U. S. Geol. Surv.)

Figs. 113 and 114, at two points in the Appalachian mountains; and Fig. 115, near Holyoke, Mass. These several sections give a fairly adequate idea of the present position and relations of the system. In Figs. 102, 107, and 112 the structure of the Cambrian is relatively simple and the rocks are not metamorphosed. In Fig. 103 the beds are gently folded and erosion has discovered the Cambrian beds at the tops of the anticlines. The rocks are not metamorphic. In Fig. 113 the beds are more crumpled at the right, and faulted as well as folded at the left, and the rocks are somewhat metamorphic. In Fig. 114 close folding and faulting are represented, and the metamorphism of the rocks has proceeded farther, though not to extremes. In Fig. 115 the crumpling due to profound dynamic action is more pronounced, and here the rocks are highly metamorphic.

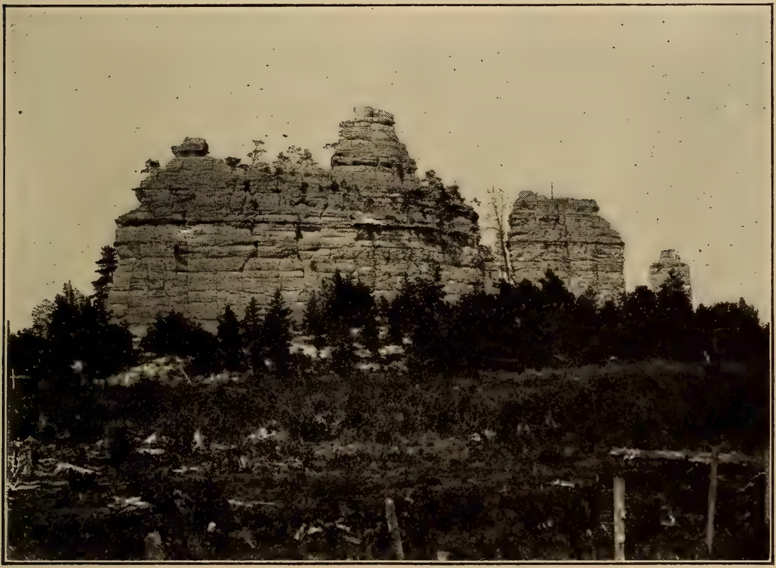

FIG. 116.—Figure showing an isolated remnant (a dying hill) of Potsdam sandstone in central Wisconsin. The remnant has been isolated by erosion.

Close of the Cambrian.—No physical changes of great importance seem to have marked the close of the Cambrian period in America. Nowhere in our continent, so far as now known, were mountains made at this time, and nowhere were great areas of sea-bottom converted into land.

FOREIGN CAMBRIAN.

Europe.[1]—The only continent besides North America which has been sufficiently studied to allow of definite portrayal of the Cambrian formations, is Europe. In the area occupied by this continent there is evidence that there was, as in North America, a somewhat widespread deformation in pre-Cambrian time, which converted large areas into land. Further, there is evidence that these lands, like those of America, were subjected to protracted erosion before the deposition of the oldest known Paleozoic formations. As a result, the Cambrian system, where its base is seen, generally rests unconformably on older strata, but in places it is so highly metamorphic as not to be readily distinguished from them. Occasionally, too, there may be real gradation into the Proterozoic formations.

The Cambrian formations of Europe, like those of America, are mainly clastic. They include conglomerates, sandstones, graywackes, shales and their metamorphic equivalents, quartzites, slates, schists, etc. In some places, thick bodies of limestone, partly or wholly metamorphosed, are associated with the clastic beds. A considerable proportion of the material involved in the clastic formations is coarse, and the strata are often ripple-marked, and affected by cross-bedding and by sun-cracks. All these features point to the conclusion that a large part of the Cambrian sediments were laid down in shallow water. In some regions the formations are notably red, a fact which has been thought to indicate that they were formed on land or in lakes or inland seas.[2]

The European Cambrian is notable for its extreme variations in thickness. In Wales (Cambria), the country from which the system received its name, it has a thickness of 12,000 feet or more.[3] This great thickness is equalled or exceeded in Brittany, where formations 8000 meters in thickness are referred to the system. In western England the thickness is 3000 feet, and in northern Scotland 2000 feet, while in

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[1] The best summary of the Cambrian of Europe, in English, is found in Geikie's Text-book of Geology, 4th ed., Vol. II. This text gives references to the literature. Other recent summaries are given in DeLapparent's, Traité de Géologie, Credner's Elemente der Geologie, and Kayser's Formationskunde.

[2] Ramsey, Quart. Jour. of the Geol. Soc., Vol. XXVII, 1871, p. 250.

[3] DeLapparent (Traité de Géologie, 4th ed., 119) assigns the Cambrian of this region a thickness of 8000 to 10,000 meters.

Scandinavia, where Lower, Middle, and Upper Cambrian all are present, the aggregate thickness is sometimes no more than 400 feet. In western Russia also it is thin. These differences probably mean that sediments were being deposited in some places many times as rapidly as in others.

The commonly accepted subdivisions of the British Cambrian are (1) the Harleck and Llanberis group (Olenellus zone), (2) the Menevian group (Paradoxides zone), and (3) the Lingula flags (Olenus zone). The Tremadoc slates are sometimes classed as Upper Cambrian.

The subdivisions of the Cambrian are notably unlike in different parts of the continent. The faunal unlikenesses are such as to seem to divide the continent into two natural provinces, a northern and a southern. To the northern division belong the areas of Cambrian rock found in Russia, Scandinavia, and north Scotland; to the southern, those found in Bohemia,[1] France, Spain, Portugal, Sardinia. It is commonly believed that some sort of barrier must have existed between these provinces which prevented marine life from passing freely between them. It has also been suggested that the differences in faunas between the two regions may be due, at least in part, to climate;[2] but this suggestion finds little support so far as present knowledge goes in other parts of the world. The fossils of the northern provinces of Europe have much resemblance to those of the Atlantic border of America, suggesting that geographic and climatic conditions were such as to allow of the free migration of marine life from northern Europe to eastern America, and *vice versa.*

In Europe the Middle Cambrian is more wide-spread than the Lower or Upper,[3] showing that changes in the relation of sea and land were in progress during the Cambrian period, shifting the areas of erosion and sedimentation. It is a matter of interest to note that the Cambrian history of western Europe seems to have some correspondence with that of eastern North America, while that of central and eastern Europe has more likeness to that of the interior of our continent.

The total area where the Cambrian rocks are exposed in Europe is small, and the outcrops sustain the same general relations to older formations as in North America. The actual extent of the system is much greater than the area where it is exposed, since it is covered in many regions by younger formations. The Cambrian, however, is not believed to underlie the younger strata of eastern Russia, and this part of the continent is believed to have been mostly out of water during the Cambrian period.

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[1] Made famous by the classic studies of Barrande; Système Silurien de la Bohême.

[2] Kayser and Lake, Comparative Geology.

[3] Frech, Neues Jahrbuch für Mineralogie, 1899, Bd. II, pp. 164–176.

The Cambrian strata of Europe, especially of western Europe, are often much folded. In some regions also (Britain and Brittany) igneous rocks occur at or near the base of the system. In central and eastern Europe, on the other hand, the formations are essentially horizontal. Beds of clay which are still plastic, and beds of sand which are still uncemented, are here found within the limits of the system.

No geographic change of great importance seems to have marked the close of the Cambrian. In this respect, as in others, the Cambrian history of Europe and North America are in general correspondence.

Other countries.—By means of their fossils Cambrian rocks are known to occur in the northeastern parts of China,[1] in the Salt range of India[2] (Lower and Middle Cambrian), in the southeastern part of Australia[3] and in Tasmania (Lower, Middle, and Upper), and in the northwestern part (Salta) of Argentina[4] (Upper Cambrian). In most of these regions the formations have not been studied in much detail.

Glacial formations.—In the vicinity of Varanger fjord, in northern Norway, Lat. 70° 8′ N., there is a bed of bowlder-bearing rock resting on a smoothed and striated pavement of the distinctive glacial type, and embraced within an irregular clastic formation, known as the Gaisa beds.[5] These beds rest upon the eroded surface of a crystalline terrane. No fossils have been found in them and their age is not positively determined. Reusch regards them as equivalent to the Sparagmite formation in central and southern Norway which underlies beds containing the *Olenellus* fauna, and which is therefore either the very earliest Cambrian or earlier. The Gaisa beds bear some resemblance to the Torridon (Proterozoic) of the British Isles and may be of the same age. They are of the red sandstone type, of which Strahan significantly remarks: "They all belong, in part, to the type prevailing in those formations which have been the first to be deposited at the close of a great continental epoch."

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[1] Von Richthofen, China, Vol. III.

[2] Redlich, Palæontologica Indica, new ser. Vol. I, and Records Geol. Surv. of India, Vols. XXII, XXIV, and XXVII.

[3] Etheridge, Proc. Roy. Soc. Tasmania, 1882–1883; Trans. Roy. Soc. Australia, Vol. XIII; Tate, *Ibid.*, Vol. II, XLVIII, and XV; and Johnston, Surv. of Tasmania.

[4] Kayser, Zeit. der deutsch. Geol. Gesell., Vol. XLIX.

[5] Reusch, Norges geologiske Undersöegelse: Det nordlige Norges Geologi, 1891 Also Strahan, Quar. Jour. Geol. Soc., Vol. 53, 1897, pp. 137–146.

Recent exploration in China[1] has shown the existence, on the Yang-tse river, in latitude 30°, of a thick formation (170 feet) of bowlder-bearing rock of the typical glacial kind containing many striated bowlders of diverse sorts of rock (Fig. 116*a*). The striæ appear to be of the distinctive glacial type and the matrix in which the striated stones are imbedded is such as bear out the evidence of the stones themselves. The formation lies at the very base of the Paleozoic terrane of the region, and beneath the series that carries the Cambrian trilobites. It is therefore to be referred either to very early Cambrian, or to pre-Cambrian time. At present, the most probable interpretation is that these formations of Norway and China belong either to the transition period that accompanied and followed the deformation that closed the Proterozoic, or to the opening stages of the Paleozoic previous to the undoubted Cambrian, with some preference for the latter. Whatever their precise age, their profound significance is obvious.

From Australia[2] and South Africa[3] Cambrian or pre-Cambrian glacial beds have been reported recently.

In the rocks of undoubted Cambrian age there is little valid evidence pointing to diversity of climate. The testimony of the fossils, wherever gathered, implies nearly uniform climatic conditions not only over our own continent, but throughout all the earth where records of the Cambrian period are found.

Duration of the Cambrian Period.

There is no way in which a reliable estimate may be made of the duration of the Cambrian period. It is safe to say that the destruction and the removal to the sea of such large volumes of rock as are represented by the sediments of the Cambrian required a very long period of time; but since there is no standard rate at which any sort of sedi-

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[1] Willis, Blackwelder, and Sargent. The above note is based on an unpublished oral statement of the results obtained during an extended exploration under the auspices of the Carnegie Institution. See also Year Book No. 3, Carnegie Inst., p. 382.

[2] Howchin and David, Rept. Austral. Assn. for the Adv. of Science, Vol. IX, 1902.

[3] Schwarz, Jour. of Geol., Vol. XIV, p. 683, 1906.

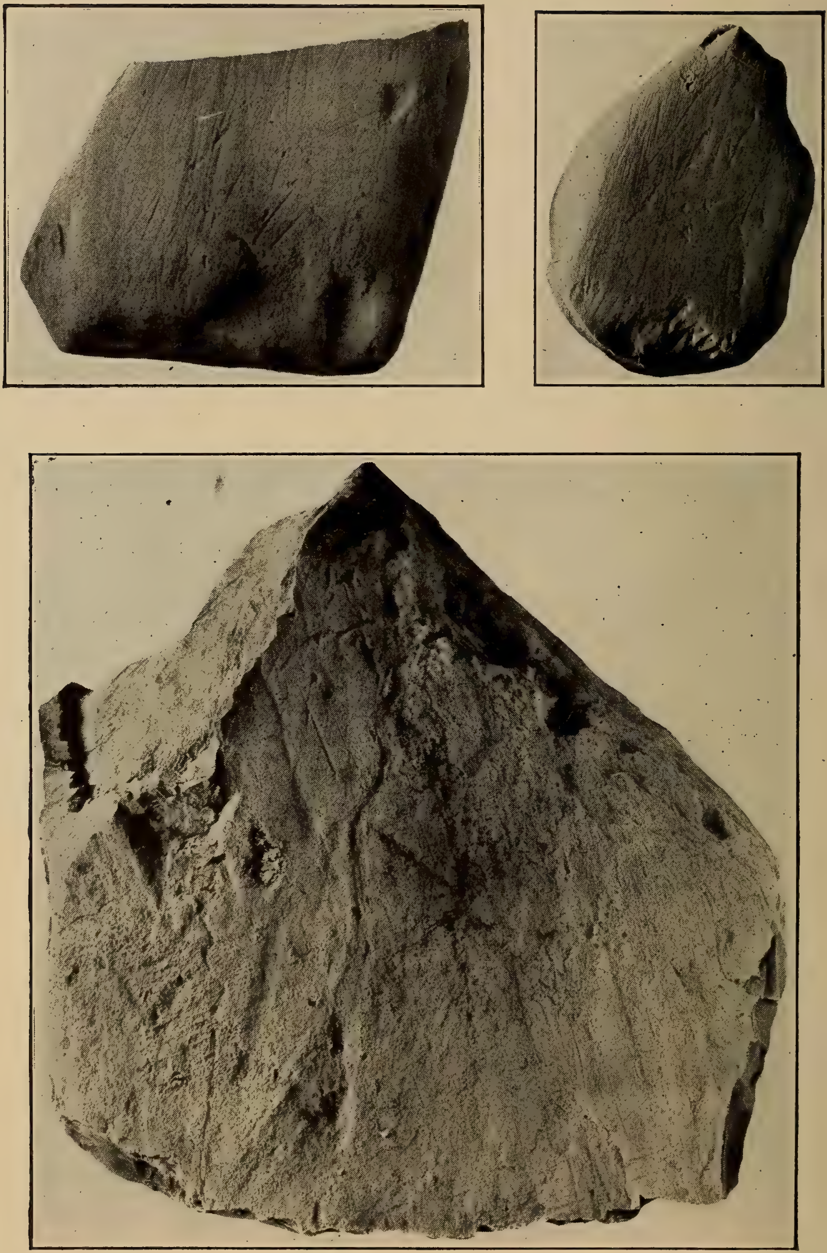

FIG. 116*a*.—Glaciated stones from the glacial beds at the base of the Cambrian in China. (Willis, Carnegie Institution.)

ment is known to accumulate, this long period cannot be reduced to years. It is quite certain that the rates vary greatly. Besides many obvious illustrations of the minor sort, there is this very general and important one: When the land is relatively broad and high, and while the deposition belt around its borders is narrow, as is apt to be the case after a period of continental protrusion, the amount of material eroded in a given time is likely to be large, while its concentration on the limited deposition area necessarily gives great proportional thickness and rapidity of rate to the accumulation. On the other hand, when the continent is approaching base-level, and the land is low and limited by the encroachment of the epicontinental seas, and while these seas are wide and shallow, and subject to agitation over broad tracts, the amount of material eroded in a given time is relatively small, while the area over which it is spread is exceptionally large, and hence it adds but slightly and slowly to the thickness of the deposits. In Washington County, N. Y., there is a bed of Cambrian limestone 1400 feet thick beneath 10,000 feet or more of fragmental rock. It has been estimated that limestone sometimes forms at some such rate as one foot per century.[1] At this rate this limestone alone would have required 140,000 years. If the overlying fragmental rocks required an equal length of time for their accumulation, the total length of the period would be 280,000 years. In some parts of the West there are 6000 feet of limestone besides thick bodies of fragmental rock. At the same rate of accumulation, the 6000 feet of limestone would call for a period of 600,000 years, and if time be allowed for the other formations of the same region, the period would be greatly lengthened. It should be remembered, however, that while one foot per century may be a rate at which limestone sometimes accumulates, it does not follow that it is the rate at which the Cambrian limestones were formed. The data on which this estimated rate is based are believed to give too high, rather than too low a rate, and a less rapid accumulation would mean a correspondingly longer period of time.

Many estimates of geological time, based on various data, have been attempted.[2] These estimates, so far as applied to the Cambrian, generally assign to that period a duration of 1,000,000 to 3,000,000 years. It should be distinctly borne in mind, however, that the chief value of these figures is to give emphasis to the fact that the period was one of great duration.

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[1] LeConte, Am. Jour. Sci., Vol. X, 1875, p. 34.

[2] For a general discussion of this matter, see Williams' Geological Biology.

THE LIFE OF THE CAMBRIAN.

Perhaps no single event in the history of the earth possesses greater interest than the first appearance of life. We have already learned that the real advent of life on the globe has not been revealed by the record, as thus far known, and there is almost no hope that it ever will be. There is good evidence that life existed in the several great periods of the Proterozoic, and in some at least of those of the Archeozoic. Under the accretion hypothesis, it is not improbable that the real beginning of life on the earth greatly antedated even the oldest of the accessible Archean formations. If so, it is quite beyond hope that the great problem of the earliest forms of life will ever be solved by direct fossil evidence. Even in the Archeozoic and Proterozoic the evidences of life, while sufficient to create a firm conviction that the earth was then tenanted by living things, are so indirect or obscure that they give very little idea of the nature of the life. Such little information as the imperfect fossils give, carries in itself evidence that it does not tell the whole story, or even the main part of it, for the life imperfectly represented could not have lived without other forms of life which are not represented.

The first fair record.—In the Cambrian, for the first time, there is a fair preservation, in fossil form, of the life of the period. Even here the record is very far from complete, but it is an immeasurable advance on the records of previous periods. Something of the interest and importance that would have attached to the earliest forms of life, had they been preserved, is therefore transferred to this first legible record. Preliminary to a review of this record, the chief ways in which it bears on questions of fundamental interest may receive a moment's consideration.

What stage of evolution is represented?—Foremost among the questions that arise is the stage of development that had been already attained by life, when thus first fairly preserved. Was the life really primitive, implying that it was not far removed from the true first forms of life, or did it bear signs of great previous evolution?

The stage of evolution attained may be estimated (1) by the degree of development of the various organic structures and functions, and (2) by the amount of divergence of the animal types.

(1) For comparison it may be assumed that the primitive forms were at least as simple as the simplest existing forms. Among these there are organisms which are scarcely more than aggregates of living protoplasm, almost devoid of any permanent and recognizable organs. There are also multitudes of plants and animals that consist of a single cell only. If these be taken as representing the nearest existing approach to primitive forms, a comparison between them and the complicated structures shown by many of the Cambrian fossils, presently to be described and illustrated, will give some impression of the degree of advance in organization that had been attained.

But we are not left entirely to this mere presumption that the earliest forms were much simpler than the Cambrian, for the stages of development of the young of certain of the Cambrian animals reveals something of their ancestral history. It is a well-established law of embryology that animals in their pre-natal and youthful development pass through a succession of stages in which their structure resembles that which their ancestors had in their maturity; in other words, that the individual history of each animal is an epitome of the collective history of its ancestors. Now the trilobites (Fig. 118), the leading form of Cambrian life, are known to have passed through a series of quite remarkable changes after they became well enough developed to be fossilized, and doubtless they passed through other stages previously. There is, therefore, specific ground for believing that they had a long line of ancestors.

(2) The studies of recent decades have convinced investigators that the later forms of life have been derived from earlier ones by some process of evolution. The exact nature of the process is yet under investigation, but the fact of derivation is not now regarded as an open question. As the various forms developed and diverged, many of the intermediate gradations were dropped out, because of inferior fitness, or from some other cause, and thus the diverging forms became separated from one another. As these divergent branches themselves developed later, they in turn diverged, and the intermediate forms disappeared, and thus a succession of branches was developed. By such continued divergence and loss of intermediate forms, a more and more complicated system of branching was developed. Not only

were the intermediate or connecting forms dropped out, but many of the branches themselves disappeared, and the remaining ones became more and more widely distinct from one another. The process was not unlike the evolution of a tree-top, in which the dying out of most of the interior branches leaves a few great limbs which bear the more numerous and more recent branches, while these in turn bear the uppermost and outermost twigs which represent the living phase. In this way, or in some such way, it is thought that the existing divergence of organisms into kingdoms, branches, classes, orders, families, genera, species, and varieties came to be established.

If it be assumed that the whole system of living things has been derived from a common primitive form or a few primitive forms, a comparison of the primitive state with the degree to which divergence, and the loss of the intermediate forms, had gone in the Cambrian times, will give some impression of the amount of evolution already accomplished. If to this be added a comparison between the Cambrian life and the present life, an estimate of the relative amount of evolution before and since the Cambrian period may be made. This will be especially instructive, as it will give some impression of the relative importance of the pre-Cambrian and the post-Cambrian portions of the earth's history, measured by life development.

To be sure, it cannot be assumed safely that the rate of evolution in early and in late times was precisely the same, or that the evolution of one branch proceeded at the same rate as that of other branches, for there certainly were marked differences; but notwithstanding this, a general and not altogether incorrect impression of the relative importance of the unknown pre-Cambrian evolution, and of the known post-Cambrian evolution may be derived, and this, notwithstanding all elements of uncertainty, is of no small value.

The scantiness of plant fossils.—On the most general inspection of the record there appears at once an obvious inconsistency in that the animal kingdom is fairly well represented, while plant remains are barely identifiable; indeed, their presence would perhaps be doubted if there were not imperative reasons for believing that they were present in abundance. As all animals are dependent directly or indirectly on plants for food, it must be supposed that plants were present in sufficient numbers not only to support the animals, but to furnish a surplus, since a portion inevitably escaped consumption by the animals. This surplus might not be worth noting if there were not specific reasons for regarding it as large. Not a few of the Cambrian animals were fixed to the bottom of the sea, and hence there must have been organic matter enough floating in the water to bring them their daily food, and this implies *a very general enrichment* of the oceanic waters with plants. Probably these were largely minute one-celled plants of the algæ type, and hence they easily escaped fossilization. The inadaptability of the lower plants to fossilization is doubtless the chief explanation of the poor representation of the plants among the Cambrian fossils.

Reasons of a physical nature have previously been given (p. 217) for thinking that the surface of the land was clothed with some kind of vegetation, and this is an additional reason for assuming a very general, if not nearly universal, distribution of plants over the surface of the globe. But there are no identifiable traces of land-plants, and but very obscure impressions of sea-plants. There are some ill-defined stem-like or frond-like impressions, commonly styled "fucoidal," that may be, in part at least, the casts of sea-weeds. A peculiar form consisting of clusters of radiating rays (*Oldhamia,* Fig. 117) is found in abundance in Cambrian rocks in Ireland, and has been referred to algæ, but the identification is not beyond question. These and a few other doubtful forms make up the whole record as thus far revealed. The lesson taught is the extreme imperfection of the fossil record.

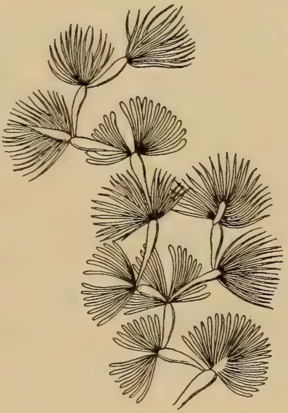

FIG. 117.—*Oldhamia antiqua* Forbes, a problematical organism most commonly referred to marine algæ, but it may possibly belong to the zoophytes.

THE ANIMAL FOSSILS.

Turning to the record of animal life, it appears by contrast that every great division of the animal kingdom, except the vertebrate, had its representatives in Cambrian times. The *Arthropoda* were represented by crustaceans; the *Mollusca,* by cephalopods, gastropods, pteropods, and pelecypods; the *Molluscoidea,* by brachiopods and bryozoans; the *Vermes,* by annelids; the *Echinodermata,* by cystoids; the *Cœlenterata,* by graptolites, medusæ, and corals; the *Porifera,* by sponges, and the *Protozoa*, by rhizopods. This is a fine array for a first appearance. As we come to study the representatives in more detail, the breadth of the divergence, and the advance in evolution that had already taken place, will appear still more impressive. These representatives are all marine forms. Of land animals there are no traces; but this negative record does not warrant the assertion that no land animals lived at this time. Terrestrial arthropods, in the form of scorpions and insects, appear in the record two periods later (Silurian), and they were then rather highly developed, which renders an ancestry reaching back as far as the Cambrian, or beyond, not improbable, though by no means certain.

No traces of vertebrates have yet been detected in the Cambrian beds, but as fish remains have been found in the rocks of the following period (Ordovician), it would be hazardous to assume that the lower aquatic vertebrates were not among the denizens of the Cambrian waters. There is no reason, however, to think that any of the terrestrial vertebrates were present.

The Cambrian Arthropoda.[1]—Of the four divisions of the Arthropoda, insects, spiders, myriapods, and crustaceans, only the last has been found in the Cambrian strata. Its representatives were trilobites and entomostraceans.

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[1] The State and Government Reports are the chief media for the description of fossils. Many descriptions are also found in scientific journals, and in the proceedings of scientific societies, and, more rarely, in private memoirs. The literature, like that on stratigraphy, is very voluminous, and cannot be fully cited in a work of this kind. A convenient key to most of the recent literature is found in Weeks's Bibliography and Index of North American Geology, Paleontology, Petrology, and Mineralogy for 1892–1903, Bulls. 188, 189, 203, and 221, U. S. Geol. Surv., which will probably be carried to later dates. References to earlier descriptions will be found in Bull. 127, U. S. Geol. Surv.

Some of the leading writers on American Cambrian fossils are: James Hall, Paleo. N. Y., Vol. I, 1847, and Ann. Repts. N. Y., 1847–1863—notably the 16th; E. Billings, Paleozoic Fossils, Geol. Surv. of Canada, 1874; J. W. Salter, Quar. Jour. Geol. Soc., 1859; S. W. Ford, Am. Jour. Sci., 1871–1881; R. P. Whitfield, N. Y. Repts., Surv. of 40th Parallel, and Wis. Repts., 1873–1879; C. Rominger, Proc. Phil. Acad. Sci., 1887; J. F. Whiteaves, Am. Jour. Sci., 1878, and Canadian Rec. Sci., 1892; A. F. Foerste, Bull. Mus. Comp. Zool., Cambridge, 1888, and Am. Jour. Sci., 1893; G. F. Matthew, Trans. Roy. Soc. Canada, 1897–1900, Trans. N. Y. Acad. Sci., 1893–96, Bull. Nat. Hist. Soc. New Brunswick, 1893–1902, and Canadian Rec. Sci., 1889–1894, and, notably, C. D. Walcott, Bulls. 10, 30, and 81, U. S. Geol. Surv., 10th Ann. Rept., U. S. Geol. Surv., Am. Jour. Sci., 1887–88, and Proc. U. S. National Museum, Vols. XI–XIII. The identifications of Walcott are chiefly followed in this work.

The *trilobites* were easily the most distinguished of the known denizens of the Cambrian seas. They were not only the highest in organization, but the most characteristic of the age. Their successive genera best distinguish the successive stages of the period, and their distribution is a chief means of correlating the formations on different continents and in different provinces of the same continent, as previously set forth (p. 240). They have hence a leading place in historical and geological importance. They belonged to a race long since extinct. A study of the accompanying illustrations (Fig. 118) will best impress their distinguishing features, notably their three longitudinal lobes, whence their name, and their three transverse divisions, head, thorax,

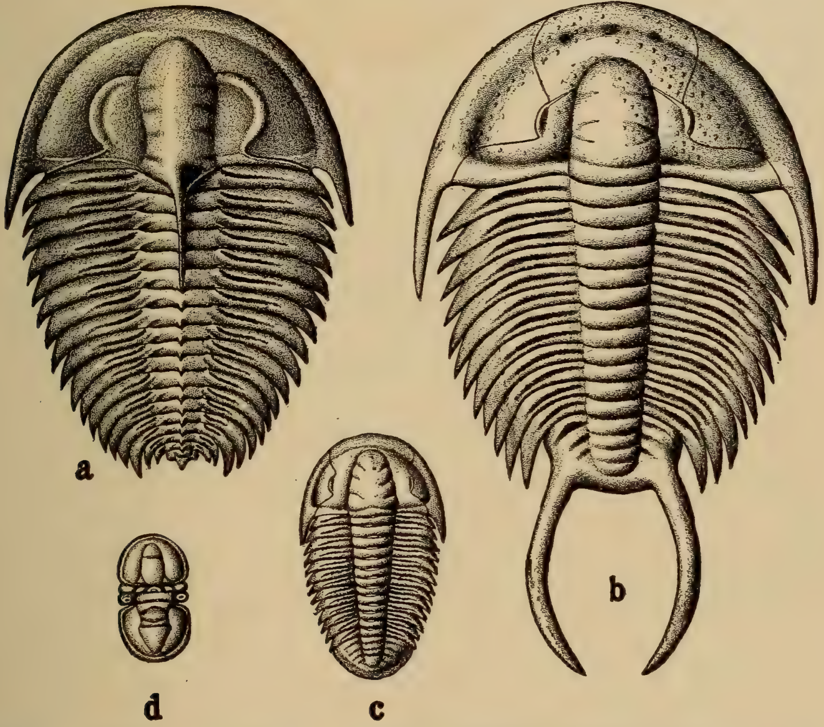

Fig. 118.—Cambrian Trilobites. *a, Holmia (Olenellus) bröggeri* Walcott, a characteristic trilobite of the Lower Cambrian; *b, Crepicephalus texanus* (Shumard), a trilobite of the Middle Cambrian; *c, Ptycoparia antiqua* (Salter), a trilobite of the Middle Cambrian. The above trilobites belong to the order *Opisthoparia. d, Agnostus obtusilobus* Matthew, a Middle Cambrian trilobite of the lowest order, *Hypoparia*, showing primitive characters, as the absence of eyes, small number of thoracic segments, etc.

and pygidium, or caudal shield. The variations of these divisions and of the other parts of their structure furnish the basis on which genera and species are founded. As the fleshy parts and the delicate understructure are wanting, the descriptions and identifications of species and genera are based solely on these harder parts. This is not exceptional. The determination of most fossil species rests on such imperfect knowledge of the real organism, but the imperfection of knowledge is being gradually reduced by the finding of forms that preserve what is lacking in those previously found. Much of the value of these, and all other fossils, in the correlation of formations in different regions, and in determining the succession of beds when not superposed, depends on the sharp discrimination of their differences of form and structure, and a critical study of the figures is recommended. In a work of this kind it is impracticable to enter upon the special description of fossils; that is the function of paleontology; but some special attention may be given to these first forms, the leaders in the great procession of life, so far as we know it.

The general aspect of the trilobites at once discloses an advanced development. It seems clear that they possessed nearly all the anatomical systems and physiological functions of modern crustaceans of their kind. In their line, they were much nearer the present end of the series than the theoretical beginning. Perhaps the eyes are the best index of their development. These show that the compound system of fixed eyes, composed of many eyelets, was already well developed. In the trilobites of this and succeeding periods, the eyelets range from a score to several thousands. Some of the Cambrian trilobites however had no eyes, never having acquired them, while others possessed abortive rudiments of eyes, implying that their ancestors had possessed eyes, but had lost them. The acquisition and abortion of so important an organ seems to imply variation in the conditions of life, but this may mean no more than migration to deep dark waters, or the habit of burrowing in the mud, where eyes became useless. The eyes were often slightly raised on crescentic lobes, with the convex face outwards. In later epochs, these crescents became more and more curved, extending the sweep of vision fore and aft to the trilobite's obvious advantage, and hence this became a mark of progress. In the Cambrian faunas, the segments of the body were rather stiffly joined to one another, but in later epochs they became more flexible and some trilobites rolled themselves up armadillo fashion—another mark of progress. The upper surface of the body was, even in Cambrian times, ornamented variously with granules, spines, and other markings, the significance of which is little understood. These ornamentations varied as time went on, increasing, in general, until after the climax of the trilobites had been passed.

The understructure is not revealed in the Cambrian specimens, the parts having been lost in fossilization, but later forms, worked out by Walcott, Beecher, and others, show that the trilobites possessed a row of slender articulated limbs on either side, and also delicate filaments which served the function of respiratory organs. The nature of the limbs indicates that the trilobites both walked and swam. It is inferred that some were swift of movement, while the weakness of the ambulatory organs in others implies that they were slow. The trilobites also possessed antennæ which doubtless served as organs of touch—another indication of the definite development of the senses, even at this early time. It is interesting to note that the habit of moulting the shell at successive stages of growth had been acquired. Leaving further details to the special study of the accompanying figures, it is to be observed that, at this early day, there had been acquired a highly complex, well-differentiated organization, endowed with nearly all the organs and functions possessed by similar crustaceans of the present day.

Besides these ancestral crustaceans, a few other forms of interest were present, among which were little ostracodes which had valve-like shells on their backs much like those of bivalve mollusks (Fig. 119, *c*), an ancient type of phyllopods represented by the singular form *Protocaris* (Fig. 119, *d*), and a phyllocarid (Fig. 119, *a* and *b*).

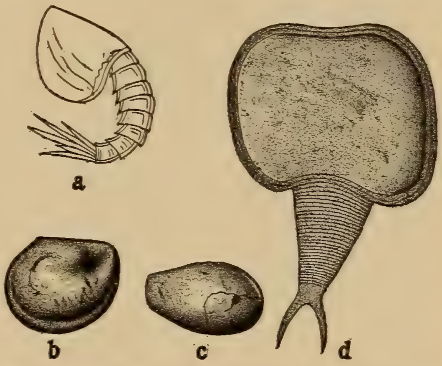

Fig. 119.—Other Cambrian Crustacea. *a*, *Hymenocaris vermicauda* Salter; *b*, *Aristozoœ rotundata* Walcott, a Cambrian phyllocarid; *c*, *Leperditia dermatoides* Walcott, a Cambrian ostracode; *d*, *Protocaris marshi* Walcott, a Cambrian phyllopod.

The Cambrian Mollusca.—A few cephalopods (chambered shells) which are regarded as the highest class of mollusks have been found in the uppermost beds referred to the Cambrian, but none as yet in the lower part. As the cephalopods were even then highly developed structurally, and were widely differentiated from the other mollusks, there is little ground to doubt that they had already passed through a long period of development, and hence that they were really present in some part of the globe during the earlier Cambrian times. Their remains are so rare that they have little geologic importance in this period, but become prominent in the next.

The pelecypods (bivalves) were represented in the Lower Cambrian beds, though they have not been found abundantly. Whether this implies that they did not live abundantly in the seas that made the deposits that are now accessible, or that they were but poorly preserved, is not known. Fig. 120, *b*, represents a typical form.

Gastropods (univalves) (Fig. 120, *c*, *d*, and *e*) were somewhat abundant even in the earlier Cambrian times, and became more common toward the close of the period. The early forms found are chiefly of the low conical type, known as capulids, from their resemblance to the form of cap typified by the conventional "liberty-cap" (see Fig. 120, *d*, in particular). The more amply coiled and spiral forms (Fig. 120, *e*), though present, only became common later. The close resemblance of *Trochus saratogensis* (Fig. 120, *e*) and other forms to modern gastropods is worthy of note as showing how near to the present development some of the Cambrian mollusks had attained.

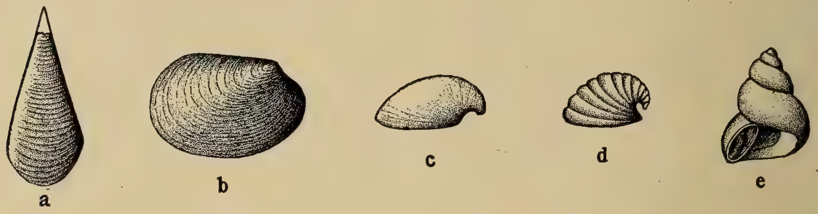

Fig. 120.—Cambrian Mollusca. *a*, *Hyolithes americanus* Billings, a pteropod of the Lower Cambrian; *b*, *Fordilla troyensis* Barrande, a pelecypod of the Lower Cambrian; *c*, *Stenotheca rugosa*, var. *paupera* Billings, *d*, *S. rugosa* Hall, capulid gastropods of the Lower Cambrian; *e*, *Trochus saratogensis* Walcott, a Cambrian gastropod with well-developed spire.

The Cambrian Molluscoidea.—This branch was well represented by brachiopods (lamp-shells), (Fig. 121). In geological importance, these rank second only to the trilobites in Cambrian times. Unlike the trilobites, which became extinct at an early day, the brachiopods have persisted to the present time, and stand as a foremost representative of extreme stability and persistence. They have changed in species and, except in a few cases, in genera also, but the class has been only slightly modified and still retains, with great fidelity, its distinctive characteristics.

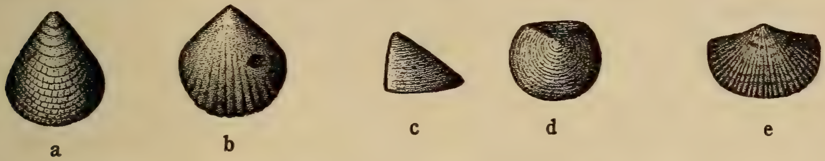

Fig. 121.—Cambrian Brachiopoda. *a*, *Obolella gemma* Billings; *b*, *Protorhyncha antiquata* Billings, brachiopods of the Lower Cambrian; *c* and *d*, *Acrotreta gemma* Billings, a brachiopod ranging from the Lower to the Upper Cambrian, summit and side views of the pedicle or ventral valve; *e*, *Billingsella transversa* Walcott, the pedicle or ventral valve of a hinged brachiopod of the Lower Cambrian.

In Cambrian times, as now, the valves of one division of the group were hinged, while those of another were not. So, too, then as now, one division formed shells of calcium phosphate, and another shells of calcium carbonate. Comparisons in other respects show that the changes between the Cambrian and the present are but a small fraction of the

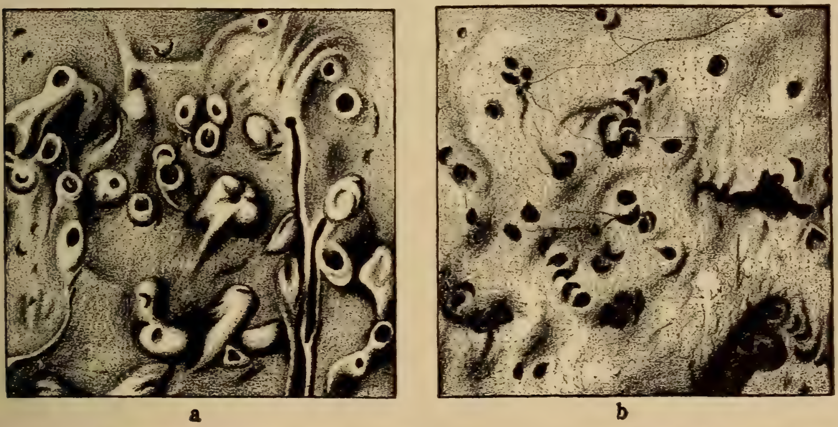

Fig. 122.—Cambrian Vermes; borings and trails. *a*, a natural surface of sandstone seen from above, showing annelid borings, with mounds of sand heaped about their mouths and with trails leading away from some of them; *b*, a horizontal section, showing perfect borings, as well as abandoned borings whose sides have been forced in during the formation of new borings, giving a crescentic cross-section. Although the animal is not shown, the name *Arenicolites woodi* Whitfield is assigned to it.

changes involved in the development of the brachiopods from the theoretical primitive forms in pre-Cambrian times. Though the brachiopods were wonderfully persistent and conservative in evolution, they were undergoing changes from epoch to epoch, and thus they became valuable indices of progress, and serviceable means of identifying horizons and correlating distinct deposits.

The Cambrian Vermes.—Sea worms, or annelids, left indications of their abundant presence by borings and tracks, and occasionally by mud or sand heapings at the mouths of their holes (Fig. 122), but no remains of the animals themselves have been found.

The Cambrian Echinodermata.—A few cystids were present (Fig. 123). They had roundish or cylindrical bodies, covered unsymmetrically with plates. Irregular arms were attached to the upper part, and a stem, often short and incomplete, was appended to the lower end. The cystids were the forerunners of the beautiful crinoids (stone lilies) which perhaps came into existence during the Cambrian times, but have not yet been found in fossil form.

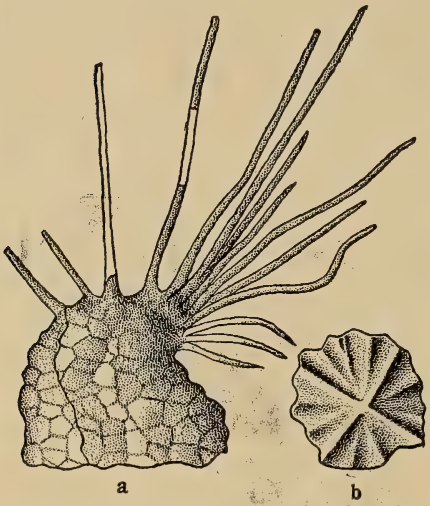

Fig. 123.—Cambrian Echinodermata. *a*, *Eocystites* (?) *longidactylus* Walcott, a view of the upper part of an imperfect Cambrian cystid, showing the irregular plates and broken arms; *b*, *Eocystites primævous* Billings, a single cystidian plate.

The Cambrian Cœlenterata.—The cœlenterates were represented by *hydrozoa* (graptolites and medusæ) and by *anthozoa* (corals), (Fig. 124). The eccentric and almost inexplicable freaks of fossilization are nowhere better illustrated than in the Cambrian relics of this group. Graptolites, although among the most delicate of animal forms, and medusæ, among the softest of animals, were preserved, while much more robust and indurated forms, that almost certainly were present, left scant relics, or none at all. The graptolites, an extinct group, were very slender, plume-like organisms, consisting of a series of cells, in which the individual animal lived, attached to a common slender axis which united the colony and which often branched much after the fashion of plants. The whole plume appears to have floated free in the sea. They were scantily preserved in the earliest Cambrian (Fig. 124, *e*), but quite abundantly toward its close. The secret of their preservation probably lies in the fact that, being floating forms, they most often settled in quiet and rather deep waters off-shore, where very fine silts accumulated, and where, therefore, the conditions were favorable for burial without destructive action.

The most singular case of fossilization is the preservation of traces of jelly-fish, or at least of what are so identified. These are illustrated in Fig. 124, *c* and *d*. Their impressions are found in the lower division of the Cambrian.

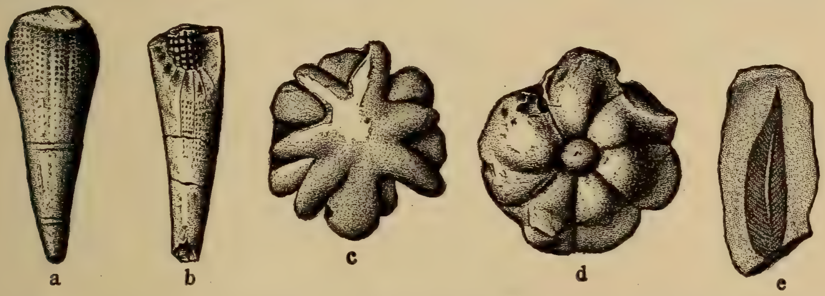

FIG. 124.—Cambrian Cœlenterata; supposed corals, medusæ, and graptolites. *a* and *b*, *Archæocyathus rensselæricus* Ford, a problematic fossil referred by some paleontologists to sponges, and by others to corals; *c* and *d*, *Brooksella alternata* Walcott, supposed casts of the gastric cavities of medusæ; *c*, a supposed exumbrella in which the interumbrella lobes are a prominent feature; *d*, a view of a supposed umbrella with six lobes and a depression over the central stomach; *e*, *Phyllograptus* (?) *cambrensis* Walcott, the hydrosoma of a graptolite.

Obscure forms of corals were also present (Fig. 124, *a* and *b*) though none of the higher types has yet been discovered. The forms found resemble sponges so much that they were long regarded as such, but recent microscopical examination by Hinde seems to show that they had a coralline nature.

True sponges were present in some abundance and ranged throughout the period. Their spicules have been sometimes found where the general form and the fibrous parts have perished.

The Cambrian Protozoa.—It is probable that many of the low simple forms classed as protozoans were present, but owing to their unsuitability to preservation as fossils, only a few identifiable forms have been found.[1]

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[1] Several are described by G. F. Matthew in "The Protelenus Fauna," Trans. N. Y. Acad. Sci., Vol. XIV, 1895, pp. 101–153.

Unidentified forms.—Besides the forms that can be identified there are some which cannot be interpreted with certainty. Among these are certain tracks found in Canada, Wisconsin, and elsewhere. Two varieties are illustrated in Fig. 125. They consist of consecutive rows of V-like forms with trail markings superposed, as though filaments or flexible organs were dragged over the impressions immediately after they were formed. The organs that made the V-like impressions were flexible, as shown by the variation in the form of the tracks, the curvature of the ridges, and the shifting of the position of the apex. The depth of the impressions and the compacting of the surface of the sand implies a rather heavy animal, or one that burrowed beneath the sand. The nature of the animal that produced them is problematical. There are other impressions that consist of rows of indentations, as though made by the feet of arthropods, while still others are continuous grooves.

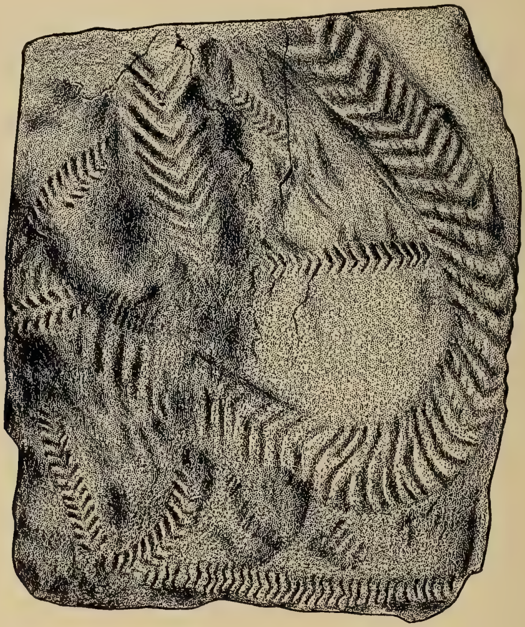

Fig. 125.—Unidentified forms. Tracks of an unknown animal found in the Upper Cambrian sandstone near New Lisbon, Wis.

Implied life.—Scientific geology, in the strict sense of the term, contents itself with considering the demonstrable forms and their immediate indications, but philosophical geology goes further and endeavors to supply such forms as may be necessary to fill out a consistent assemblage of life. It has already been noted that the presence of so much animal life implies much vegetable life to supply the necessary food. This inference is almost as firm as the inference that the fossils really represent organisms that once lived, which was once questioned, but is now regarded as a scientific conclusion. Firm inferences, like that of the presence of abundant vegetation in the Cambrian, grade away insensibly into others that are weaker and weaker until they become very infirm. There is hence a danger of extending philosophical geology until it shall pass into speculative geology, without being fully aware of the fact. Great circumspection is needed when the field of free inference is invaded, but the subject of ancient life would be left barren of half its interest, and most of its stimulus, if inferences were not indulged in their proper places and to their proper degrees. The need of caution arises more largely perhaps from unrecognized alternatives than from any other single source. For example, in the inference relative to vegetation in the Cambrian and pre-Cambrian times, which seems so imperative, it is barely possible that an early form of life intermediate between plants and animals, or combining their qualities, and ancestral to both, may have lived in the earliest ages, and have possessed the power of organizing organic matter from inorganic matter. These may have furnished the ulterior food of the animals, instead of plants, which may have been differentiated from them later. And so even the strong case of inferring vegetation from the presence of animals is not without some small occasion for reserve. But this is really only a change in the form of the inference rather than in its real substance, which is that Cambrian animals imply the existence of plants or of unknown organisms that performed the chemical functions now performed by plants.

Duly mindful of the weaknesses and dangers of pressing inferences too far and duly appreciative of their stimulative value when properly controlled, we may inquire how far the forms and functions of the known Cambrian animals suggest the existence of other animals whose presence is not recorded. A large percentage of the known Cambrian animals were provided with shells, tests, plates, or other forms of hard coverings. In the main these appear to have been protective devices, and imply enemies or combative rivals against which the protection was needed. Can the known Cambrian animals have constituted such enemies, or must others be supposed to have existed to furnish a good reason for such protective provisions? Perhaps the most significant feature of the protective devices lies in the fact that they are usually of the same type as those possessed by the corresponding animals of later times. The shells of the gastropods, pelecypods, and brachiopods differ from those of to-day only in minor features. The coverings of the trilobites are very much the same as those of their crustacean relatives in existing seas. Much the same may be said of nearly every form. If there had been a radical change in the character of their enemies or rivals, we might expect some notable change in the defensive devices. It is a natural inference, therefore, that the conflicts of life in the Cambrian waters had become very much what they have been in later times. The inference may be pushed a step further, and the deduction drawn that the conflicts which led to the evolution of the defensive devices were much the same that they have been throughout the period of their retention. If the reign of the great predaceous mollusks, the cephalopods, and that of the predaceous fishes be supposed to have reached back through the Cambrian period to the time when the armorings of the various forms were acquired, the total assemblage of attackers and defenders in the seas would have been very much the same as it is now, for the marine reptiles and mammals that have come in since have not essentially changed the nature of the conflict. The occurrence of the cephalopods in the closing stage of the Cambrian, and of the fishes in the succeeding Ordovician period, removes any special improbability from the hypothesis that they were present in the early Cambrian, and perhaps even earlier.

If the defensive devices of the Cambrian animals are to be explained within the strict limits of the known forms, the armor of the large trilobites must apparently be regarded as a defense against members of their own race, for no other known animal apparently had sufficient celerity of motion and sufficient strength to give occasion for such protection. A similar remark may be made of the great cephalopods when they came in toward the close of the period. The protection of the gastropods, pelecypods, brachiopods, etc., of the early Cambrian may have been needed as a defense against the trilobites, but it is not at all clear that just such coverings as they had were specially adapted to defend them against the trilobites, as we should expect them to be if evolved for this special purpose.

While final conclusions can scarcely be reached by such studies, they lend interest to the study of the parts which are chiefly fossilized and throw a little light on the life of these early inhabitants of the globe.

Sociological development.—If sociology be defined as the relationship of one living thing to others, the relations of attack and defense may be said to constitute the militant phase of the sociological development of the Cambrian times. These beginnings of animal sociology possess no small interest and importance, however crude they may seem to be, if we entertain the doctrine of evolution in its broader phases which embrace mental as well as physical evolution. The adjustment of the organisms to one another and the development of qualities, physical and mental, suited to such adjustment, is a subject applicable to all the ages in which conscious life prevailed, and the simple lessons of its crude beginning may not be less instructive than the more intricate ones of the late stages. The early evidence, to be sure, is imperfect, and the interpretation is by no means sure, but it nevertheless merits attention.

The shells of trilobites are sometimes found together in large numbers. Occasionally they are closely packed, "spoon-fashion." Not unlikely these may be the molted shells, for the habit of molting had been acquired even at this time. Possibly the assembling of the shells may be the work of currents or similar inorganic agencies, but the suggestion that the trilobites were gregarious, either habitually or seasonally, may be entertained. Obscure and uncertain as these and similar suggestions may be, we shall not have followed the history of life development far before the evidences of social relations will be distinct and unmistakable.

Mental development.—The wars of the Cambrian inhabitants, implied by their weapons of offense and defense, can scarcely have been unaccompanied by some notable measure of mental development, however the nature of such development may be interpreted. That the trilobites sought their food or pursued their prey by sight, and were guided by touch, their eyes and their antennæ imply, and it is difficult to conceive of these actions without the mental processes that usually attended on pursuit and capture. The control of so complex and active an organism as that of the trilobite implies an excellent development of the nervous system. It is not safe to attempt to say how far this admirable mechanism was directed by conscious intelligence, as distinguished from what we choose to call automatic or instinctive action, but there is food for thought in placing ourselves face to face with the alternative of either assigning these fine organisms and their complex activities to unconscious automatism, or else of recognizing in them the early stages of conscious psychology. Whether our interpretations be wholly correct or not, it is better to give a passing thought to these higher problems than to ignore one of the most vital phases of life-evolution.

Ecological adaptations.—A study of the distribution of the Cambrian fossils gives indications that then, as ever since, there was an adaptation of life to its immediate physical environment. The life appears to have varied with the nature of the bottom, with the depth of the water, and with other marine conditions, much as it does to-day. There were mud-bottom faunas, sand-bottom faunas, and like adaptations. There seem to have been zones of shore life (littoral), of off-shore life (photobathic), and of deep-sea life (pelagic and abysmal), although the evidence of the last is scant. It is important to recognize these variations in the comparison and correlation of faunas, for considerable differences may occur among faunas which were strictly contemporaneous. Except in the case of floating forms, that are relatively indifferent to the bottom, it is usually possible to judge of the nature of the conditions under which the animals lived from the nature of the sediments in which the fossils are imbedded.

Zoölogical provinces.—The assemblages of the life of the period seem to have varied in a broader way, giving rise to zoölogical provinces. The leading agents in developing these provinces were probably barriers that isolated certain portions of the sea from other portions. The isolation was not complete in most cases, but reached such a degree of separation as to cause the life of each area to develop along its own lines, in more or less independence of the evolution of other regions. The leading principles involved have been set forth in Volume I, pp. 663–672, particularly in that portion which relates to provincial and cosmopolitan evolution, pp. 668–672.

The early faunas of the Cambrian were somewhat provincial in nature, though the provinces appear to have been large. Toward the close of the period, as the seas crept out upon the face of the continents, there was a marked tendency toward cosmopolitanism. The impression that life was everywhere the same at a given stage in the early ages, which naturally arises from the very general and limited treatment of the faunas to which works of this kind are confined by their limitations of space, is to be guarded against. There was probably less variation in the life of the different regions, during most of the geological epochs, than there is to-day, but it is not certain that this was true of all past epochs, and in none of them was there probably anything like complete uniformity over the whole globe, though there was, at times, much tendency in that direction, as implied by the term cosmopolitanism.

Comparison of pre-Cambrian and post-Cambrian evolution.—After this summary review of the Cambrian life, it is appropriate to return to the question raised at the outset relative to the degree of development which this first well-preserved fauna exhibits. On the anatomical and physiological side, it is clear that nearly or quite all the fundamental organs had been developed. There were skeletal systems of several forms; there were muscular systems, as shown by the impressions and protrusions on shells and as implied by the articulate structure of the trilobites; there were nervous systems, as implied by eyes and other evidences of sense-organs, and by the need for muscular control; there were organs for capturing and ingesting food, and hence, almost certainly, organs of digestion, secretion, excretion, and respiration; in short, there were practically all the great anatomical and physiological systems now possessed by animals. The Cambrian animals had acquired the various modes of life possessed by existing animals of their kind, as well as the various modes of preserving their lives. It is probable that all, or nearly all, the senses had some development, though this cannot be proved for certain senses. The eyes of the trilobite show that that wonderful organ was already developed in a notable degree.

In the evaluation of these evolutions it is not to be overlooked that the *initiation* of all these structures and functions is involved.

In the matter of the divergence and the isolation of classes, and the establishment of type forms, it is to be again noted that not only were all the animal subkingdoms, save perhaps the vertebrate, present, but that, in many of them, the forms had come to have so nearly the aspect of present forms that the classes and some orders are readily recognized.

The concrete question then arises, How does the initiation and the divergence of the structures and of the types that preceded the Cambrian stage compare with the developments since? The answers given by expert students of life-development very naturally vary, but, so far as known to us, they all assign a decidedly greater value to the pre-Cambrian than to the post-Cambrian evolution. Formulated in numerical terms, from sixty to ninety per cent. of the whole evolution is attributed to pre-Cambrian times.

The Succession of Faunas.

Under the doctrine of evolution, it is presumed that the life of every past stage has grown out of that which immediately preceded it, and that it has merged into that which immediately followed it. It is usually assumed that if no exceptional influences affected the process, there was a continuous series of slow changes without sharp lines of demarkation. If this conception were realized in fact, it would be less appropriate to speak of a succession of faunas than of one continuous ever-changing fauna. It is not yet demonstrated, however, that evolution proceeded solely by very slight changes coming in from generation to generation. A doctrine of evolution by distinct and abrupt mutations has recently been advanced by DeVries.[1] This maintains that changes as great as those usually regarded as distinguishing species may take place between parent and offspring, and that the new characters so introduced may be perpetuated and remain permanent. This is equivalent to maintaining that new species may arise abruptly when the parent form is in what is termed the mutating stage. It is not held that these changes take place in all species at all stages, but only in some species at certain periods of their existence when they are in this mutating condition. The doctrine, as at present held, does not maintain that a whole fauna would be likely to change into a different fauna abruptly, but merely that new species might arise in it abruptly. At present the doctrine rests chiefly on observations and experiments made on a few plants. It remains for more extensive experimental studies to substantiate or overthrow this most important doctrine. While awaiting the fate of this and cognate biological doctrines, it is to be noted that the geological record, as now known, does not show a complete gradation from one species into another, though this may be due, as commonly assigned, to the imperfection of the record. In some cases there is a close approximation to a graded series from one species to another, but the steps of the gradation are not sufficiently close and definite to decide between evolution by an infinite number of small changes, and a more abrupt change, masked more or less by variations, as postulated by the mutation theory.

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[1] Die Mutationstheorie, 1903. See also Bateson's Materials for the Study of Variation, 1894; and W. B. Scott, On Variations and Mutations, Am. Jour. Sci., 1894, p. 355.

If we turn from species to faunas, which embrace a large number of species belonging to quite different orders, it is obvious that a more general point of view must be taken, and that inferences connected with biological and physical environment, such as set forth in Volume I, pp. 663–672, are to be brought under study. As a matter of observation, it appears that sometimes one fauna graduates into the succeeding one, while at other times the change is apparently abrupt. If the progress of life the world over could be studied as a unit, it would probably appear that there was a nearly perfect gradation of the life of one stage into that of the next. This gradation probably took place more rapidly at some times than at others, and it is quite certain that some forms changed much more rapidly than others. But when we limit our study to the succession of life of any one continent, or to that of its coasts or embayments, or to that of some one of the seas on its borders or on its bosom, or to that of any limited province, it is evident that the progress of evolution in the given region was subjected to interruption by physical changes, such as affected the depth, temperature, or clarity of the water, the nature of the bottom and like elements of the local environment, and that these brought about shiftings in the distribution of life. Out of these local influences superposed on the general progress of life there grew rather definite stages of change between which the faunas retained a rather constant and distinctive aspect, though always undergoing some modification. Where the change is found to have been abrupt and there is no evidence of a break in the record, the explanation is usually to be sought in migration, by which a new fauna came in from somewhere else and the old fauna emigrated to a new field, or was overwhelmed by the invaders. Comparatively slight changes in the relations of sea to land were competent to introduce or to remove barriers and to permit such migratory movements (see pp. 668–672, Vol. I). The whole process is closely analogous to the well-known succession of the human races that has been brought about by the migrations of man in the Old and New Worlds.

Pondering upon these agencies, it becomes clear that in the study of faunal progress there is occasion to recognize (1) rather abrupt changes brought about by overwhelming invasions; (2) less abrupt changes brought about by the more gradual inflow of foreign species, and the gradual commingling of the immigrants with the resident species; (3) very gradual changes, or nearly constant states, due to the slow evolution of resident species when not much affected by immigration or by physical changes; and (4) more rapid evolution due to profound changes in the physical conditions or in other agencies affecting the life, including perhaps the unknown causes that may have brought about a mutating stage simultaneously in large numbers of the leading species.

The greatest of the faunal changes are those that mark the close of "Eras" and of the greater "Periods" (using these terms in their technical senses); but within the "Periods" there were less radical changes that marked off the lesser successions of the faunas. Within the Cambrian period, three stages in the life progress are recognized and these are made the ground for distinguishing the Lower (or *Olenellus*), the Middle (or *Paradoxides*), and the Upper (or *Dikellocephalus*) fanuas of the period. It is to be understood that there were not a few species which lived from one stage into the next and constituted bonds between the faunas, and that the demarkation is not very distinct, but there were leading forms that were confined to the individual stages and characterized them and their faunas.

The Lower Cambrian or Olenellus fauna.[1]—The most characteristic genus of the lower fauna is the *Olenellus*, a finely developed trilobite of which three types are illustrated herewith, *Olenellus gilberti* (Fig. 126, *b*), *Holmia* (*Olenellus*) *bröggeri* (Fig. 118, *a*), and *Mesonacis* (*Olenellus*) *vermontana* (Fig. 126, *a*). All

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[1] See The Fauna of the Lower Cambrian or Olenellus Zone, by Chas. D. Walcott, Tenth Ann. Rept., U. S. Geol. Surv., 1888–89, and the papers therein referred to. Mr. G. F. Matthew, who has given much study to the Cambrian faunas of the Canadian provinces, interprets the succession somewhat differently from Walcott, who is here followed. See Matthew's papers referred to in foot-note, p. 280.

of these were formerly placed under the genus *Olenellus*, but the last two are now generally recognized as separate genera, and are highly characteristic of the Lower Cambrian horizons. *Holmia* is found in the coast province, and in Europe, notably in Sweden; it occurs rarely in the Appalachian province. *Mesonacis* is found in both the Appalachian and coast tracts. *Olenellus gilberti* (Fig. 126) is a typical form found in the western provinces. *O. Thompsoni* occurs in the Appalachian tract. The lowest order of trilobites (the *Hypoparia*) is represented by *Microdiscus speciosus* (Fig. 126, *c*). Its primitive characters are shown in the apparent absence of eyes, the small number of thoracic segments, and its similarity to the early stages of the higher trilobites. At least fifteen genera of trilobites, represented by fifty species, have already been found in the Lower Cambrian of America. Of brachiopods at least ten genera and thirty species are known, and many more will doubtless be found. Among the characteristic forms are *Kutorgina cingulata* (Figs. 126, *d* and *e*), *Iphidea labradorica var. swantonensis* (Figs. 126, *f* and *g*), *Protorhyncha antiquata* (Fig. 121, *b*), *Obolella gemma* (Fig. 121, *a*), *Billingsella transversa* (Fig. 121, *e*) and *Acrotreta gemma* (Fig. 121, *c* and *d*), and *Lingulella cœlata* (Fig. 126, *i*). Of gastropods, at least a half-dozen genera and a dozen species are known, among which were *Stenotheca rugosa* (Fig. 120, *c* and *d*), and *Platyceras primœvum* (Fig. 126, *h*), characteristic forms. Among the typical pelecypods was *Fordilla troyensis* (Fig. 120, *b*). A quite common

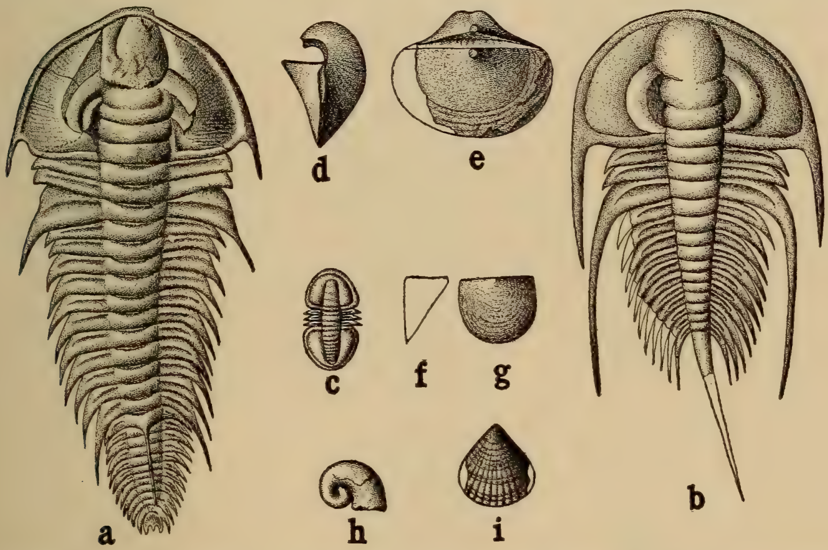

Fig. 126.—Lower Cambrian Fossils. *Trilobites: a*, *Mesonacis* (*Olenellus*) *vermontana* Hall; *b*, *Olenellus gilberti* Meek; *c*, *Microdiscus speciosus* Ford; *Brachiopods: d* and *e*, *Kutorgina cingulata* Billings, side and dorsal or brachial views; *f* and *g*, *Iphidea labradorica*, var. *swansonensis* Walcott, dorsal or brachial valve and cross-section; *i*, *Lingulella cœlata* Hall; *Gastropod: h*, *Platyceras primœvum* Billings.

fossil all through the Cambrian was the *Hyolithes,* usually referred to the pteropods. *H. americanus* (Fig. 120, *a*) was one of many Lower Cambrian species.

There were forms usually referred to sponges, but identified by Hinde as corals, such as *Archæocyathus rensselæricus* (Fig. 124, *a* and *b*) and hydrozoa, such as *Phyllograptus cambrensis* (Fig. 124, *e*). Fig. 124, *c* and *d*, *Brooksella alternata,* represent a series of singular forms regarded by Nathorst and others as the casts of the gastric cavity of a medusa.[1] There were worm-borings, tracks, and unidentifiable forms, making up, altogether, a rather varied fauna.

The Middle Cambrian or Paradoxides fauna.—The general aspect of the fauna of the Middle Cambrian was similar to that of the lower division. There was but slight evidence of advance in organization, and as knowledge now stands, no increase in numbers, but apparently a decline, which is probably merely a defect of the record. The *Olenellus* had disappeared and the *Paradoxides* (Fig. 127, *a*) reigned in its stead. The trilobites appear to have reached their climax in size in certain species of the *Paradoxides,* some individuals attaining a length of a foot and a half, but there was further advance in structure and numbers in the

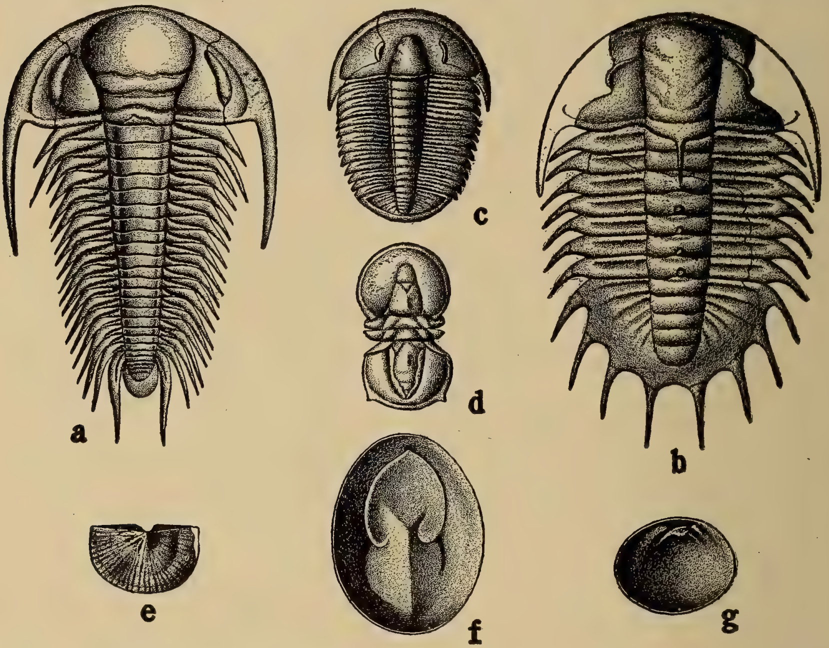

Fig. 127.—Middle Cambrian Fossils. *Trilobites: a, Paradoxides bohemicus* Boeck; *b, Olenoides curticei* Walcott; *c, Ptychoparia kingi* Meek; *d, Agnostus interstrictus* White; *Brachiopods: e, Protorthis billingsi* (Hartt); *g, Linnarsonia transversa* (Hartt); *Gastropods: f, Harttia matthewi* Walcott, interior of the shell.

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[1] For a special discussion and numerous illustrations of these forms, see Fossil Medusæ, Mono. XXX, U. S. Geol. Surv., 1898, by Walcott.

succeeding epochs. *Crepicephalus texanus* (Fig. 118, *b*) and *Olenoides curticei* (Fig. 127, *b*) are interesting trilobites belonging to the middle fauna. *Ptychoparia kingi* (Fig. 127, *c*) and *P. antiqua* (Fig. 118, *c*) are species characteristic of the middle stage, but the genus ranges both below and above. *Agnostus interstrictus* (Fig. 127, *d*) and *A. obtusilobus* (Fig. 118, *d*) represent the lowest type of trilobites. Brachiopods, as before, were next to the trilobites in importance. *Protorthis billingsi* (Fig. 127, *e*) and *Linnarssonia transversa* (Fig. 127, *g*) are distinguishing species. *Acrotreta gemma* (Fig. 121, *c* and *d*) and some other species of the lower fauna lived through the middle and into the upper stage. *Harttia matthewi* (Fig. 127, *f*) represents an interesting gastropod of the time. *Hyolithes,* representing the pteropods, were common; other pteropods were few. Plates of cystidians (*Eocystites primævus,* Fig. 123) have been found, but no complete forms.

The fauna as here characterized is that which prevailed in the Atlantic province. In the interior and western province, no very distinct Middle Cambrian fauna has been detected and the life of that stage does not seem to have closely corresponded to that of the Atlantic province.

The Upper Cambrian or Dikellocephalus fauna.—The most characteristic trilobite of the Upper Cambrian of America is the *Dikellocephalus,* while in Europe it is *Olenus,* though *Dikellocephalus* occurs there. The *D. pepinensis* (Fig. 128, *a*) is a typical species. There were many smaller trilobites, among which were species of *Ptychoparia, Conocoryphe, Crepicephalus, Agraulus,* etc. Brachiopods were well represented by phosphate linguloid shells, of which *Lingulepis pinniformis* (Fig. 128, *e* and *f*) and *Obolella polita* (Fig. 128, *g*) may be taken as typical, and by shells of calcium carbonate of which *Plectorthis newtonensis* (Fig. 128, *b* and *c*) and *Billingsella coloradoensis* (Fig. 128, *m* and *n*) are examples. The *Hyolithes* (Fig. 128, *d*) were still common. Gastropods were abundant in favorable localities, and were represented by shells of the cap type, by those coiled into a spire, as *Holopea sweeti* (Fig. 128, *h*), by those coiled in a plane, as *Bellerophon antiquatus* (Fig. 128, *i* and *j*), and by those having a depressed coil, as *Ophileta primordialis* (Fig. 128, *k* and *l*). Pelecypods and cephalopods were rare; as were also corals and cystoids. Annelids are quite frequently represented by borings and occasionally by mounds heaped about the openings of these and by trails leading away from them, as shown in Fig. 122. Greensand (*Glauconite,* a silicate of potash and iron) is rather abundant in certain horizons of the Upper Cambrian. As much of the glauconite of later beds is associated with rhizopod shells, and is now forming in connection with them, the abundant presence of rhizopods in the Upper Cambrian is inferred. Near the summit of the Cambrian series, as it is usually defined, graptolites (Fig. 124, *e*) become abundant and wide-spread, and characterize a horizon known as the *Dictyonema* beds.

The foreign Cambrian faunas.—There is a rather close correspondence between the faunas of the eastern American province and those of the western and southern European provinces, which is but another way of saying that the faunas around the border of the North Atlantic were much alike. Those of the interior and western portion of America appear to have been more nearly correlated with the faunas of central and eastern Eurasia. Richthofen found typical Cambrian fossils in eastern China, and his observations have been confirmed and extended recently by Willis and Blackwelder. Fossils of the Cambrian aspect, but somewhat divergent from the European types, occur in the Salt range of India, while more typical forms, embracing *Olenellus* and *Dikellocephalus,* are found in south Australia and Tasmania. The Upper Cambrian fauna is found in northern Argentina. Taken altogether these facts show that the same general types of life prevailed throughout the world, so far as known, while there were notable provincial variations then, as at all later stages.

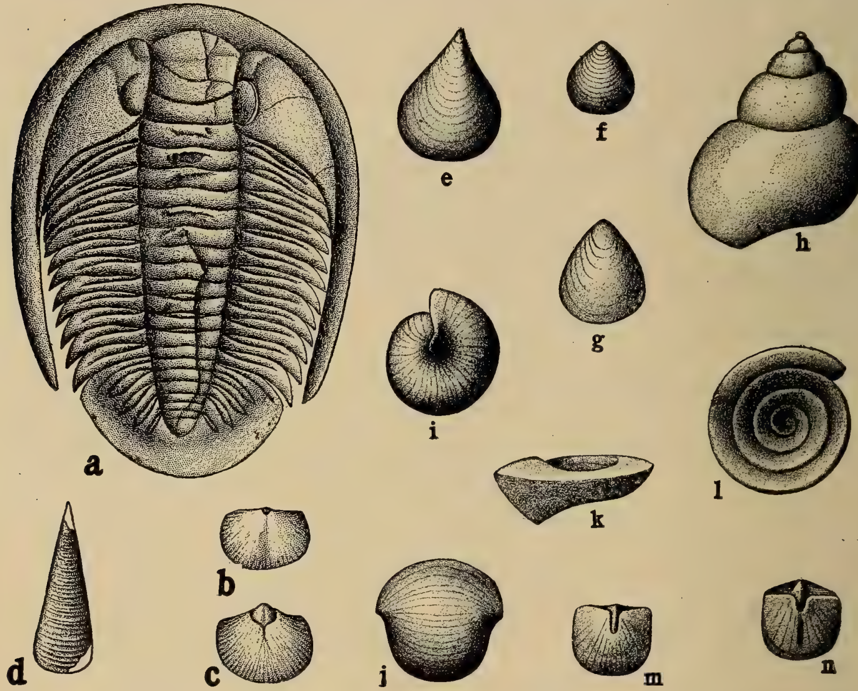

Fig. 128.—Upper Cambrian Fossils. *Trilobites: a, Dikellocephalus pepinensis,* Owen. *Brachiopods: b* and *c, Plectorthis newtonensis* Weller, internal casts of the brachial or dorsal and pedicle or ventral valves; *e* and *f, Lingulepis pinniformis* Owen, views of the two valves; *g, Obolella polita* Hall; *m* and *n, Billingsella coloradoensis* (Shum.). *Gastropods: h, Holopea sweeti* Whitfield; *i* and *j, Bellerophon antiquatus* Whitfield, two views of the same shell; *k* and *l, Ophileta primordalis* Winchell, two views of the same shell. *Pteropod: d, Hyolithes.*

The abrupt appearance of the Cambrian fauna.—The explanation of the apparent suddenness of the appearance of the Cambrian fauna is one of the open questions of geology. In a general way, it may be said that the previous beds were subjected to distortion and metamorphism and that this was liable to destroy any fossils that might have been preserved; but this is not wholly satisfactory, for some of the earlier beds are not greatly changed, and seem quite capable of receiving and retaining organic impressions. In later formations that have been considerably disturbed and changed, fossils are sometimes retained. It is equally true that later beds that seem quite capable of receiving and retaining organic impressions are devoid of them. On the whole, geologists seem inclined to refer the scantiness of pre-Cambrian fossils, and hence the apparent abruptness of the introduction of the Cambrian fauna, to unfavorable conditions for fossilization, combined with subsequent changes in the rock. This makes the abruptness merely a matter of preservation, not of evolution or real introduction. Two suggestions have, however, been made which entertain the thought that the coming of the Cambrian life into the shallow seas about the continents, and the taking on of its characteristic forms, were really, in some measure, abrupt, though the general evolution of life elsewhere and under other conditions had long been in progress.

Brooks' hypothesis.—The first of these[1] postulates that the earlier forms of life originated in the surface-waters of the open ocean, as one-celled organisms, and that, because of the simple and monotonous conditions there prevalent, the pelagic plant life has remained simple and unicellular in the main to the present time and still constitutes the chief food of all marine animals. There was little occasion for unicellular organisms to develop into aggregated forms, for in the water separate cells had larger contact with the food-supplies and with the sunlight than aggregated cells. It was only when the life became attached to the bottom or shore, or crept out upon the land, that aggregation of cells and the development of complex organisms became a marked feature in evolution. At first the conditions were unfavorable for life-development on the land and on the sea-borders;

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[1] W. K. Brooks, The Origin of the Oldest Fossils and the Discovery of the Bottom of the Ocean, Jour. Geol., Vol. II, 1894, pp. 455–479. Some features have been here added to the hypothesis.

for under this hypothesis the land was still barren and its waters were wholly sterile so far as food for animals was concerned. Besides, on account of the unprotected nature of the land surface, the wash was unrestrained and the waters were doubtless uncommonly silty. As a result, the sea waters about the borders of the land were at once sterile and muddy, and hence uninviting to most marine animals. It was only as the plants spread to the shores and crept over the land that the shore waters became clear and enriched in organic material. When at length vegetation made the shores and shallow waters congenial homes for animals, they are thought to have planted themselves there and to have evolved types adapted to that environment with relative rapidity.

The second hypothesis.—The other suggestion involves an opposite point of origin and an opposite direction of distribution. It assumes that the first forms of life were simple plants that originated in the land waters. In this, appeal is made to the observation of botanists that the fresh-water plants are of more germinal and plastic types than the marine plants and are apparently better suited to differentiate into the present rich and varied vegetable kingdom. They were better situated for this since the great differentiations of the vegetable kingdom have taken place chiefly on the land. This hypothesis further assumes that the early animals, to a greater or less degree, had their origin in the same waters, and like the plants on which they were dependent spread thence to the sea and out upon the land. It is conceived that there might be considerable development of the aquatic forms of animal life, such as the fishes,[1] mollusks,[2] crustaceans, etc., in the land waters before they became denizens of the seas, and their appearance in the latter might be at some rather advanced stage of their evolution and hence be seemingly sudden. As has been noted, it was only after the ocean waters were plentifully enriched in vegetable matter that the stationary forms of marine life could be sufficiently supplied with food. This enrichment, however, does not necessarily imply a very great period, geologically speaking.

It is doubtful whether either of these suggestive hypotheses recognizes sufficiently the fact that a great evolution of ancestral forms must apparently have taken place in a common body of water, and in close association with one another, for their defensive coverings are good evidences that they had lived and battled together long enough to evolve these and all the structures, habits, activities, and dependencies that go with them.

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[1] T. C. Chamberlin, On the Habitat of the Early Vertebrates, Jour. of Geol., Vol. VIII, 1900.

[2] F. W. Sardeson, The Phylogenic Stage of the Cambrian Gastropoda, Jour. of Geol., Vol. XI, No. 5, 1903.

CHAPTER VI.

THE ORDOVICIAN (LOWER SILURIAN) PERIOD.

FORMATIONS AND PHYSICAL HISTORY.

THAT no considerable physical change took place in the relations of land and water in North America at the close of the Cambrian period as usually defined is shown by the general conformity between the Ordovician and Cambrian systems. Where unconformity exists, it is relatively slight. There is here no considerable "lost interval" during which the record of sedimentation is unknown, and the map which shows the relations of land and water in our continent at the close of the Cambrian (Fig. 95) serves also to indicate their relations at the opening of the Ordovician.

It has been seen that during the Cambrian period, so far as North America is concerned, the sea slowly encroached on the land. During the Ordovician period which followed, the climax of the transgression was reached, and an epicontinental sea (Vol. I, p. 11) stood over much of the continent (Fig. 129). This general statement is not to be construed to mean that the continental area was altogether without movement during this period. There is reason to believe that temporary and local oscillations of level, either of the land or of the sea, or of both, sufficient to change conditions of sedimentation, were repeated many times and in many places during the period, and that at its close, geographic changes of great importance took place.

SEDIMENTATION DURING THE ORDOVICIAN PERIOD.

So long as the sea was encroaching on the land, as in the Cambrian period, the sediments deposited within the continental area were predominantly clastic. Deposits of organic sediments (shells, coral, etc., and their comminuted products), together with more or less land-derived detritus, were being made in the clearer waters beyond

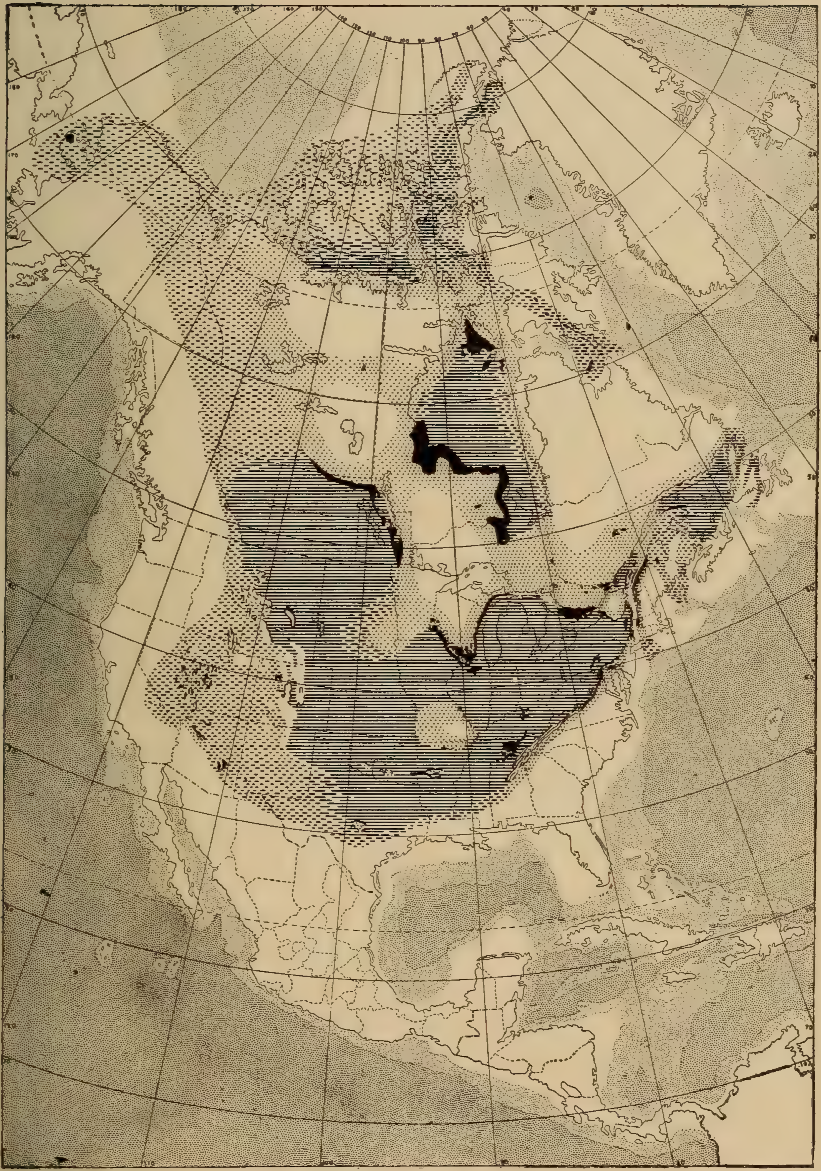

FIG. 129.—Map showing the general condition of the North American continent in Mid-Ordovician (Trenton) time. The black portions represent areas where the Middle Ordovician beds appear at the surface. These areas so nearly correspond with the areas where the Ordovician system as a whole appears at the surface that no serious error is involved if the black areas be interpreted as Ordovician The various conventions of the map are the same as in Fig. 38, p. 147.

the reach of abundant terrigenous sediments; but within the limits of the North American continent such formations were relatively unimportant.

The conditions of sedimentation during the Ordovician period were somewhat different from those of the Cambrian period. Upon such lands as still remained, the winds, the rains, the changes of temperature and the plants and animals, if then present, operated, weathering the rock and preparing it for removal to the sea. But the diminished area of the land within North America was attended by a decrease in the amount of terrigenous sediment transported to the sea, while the increased (though still shallow) depth of the epicontinental waters tended to prevent its transportation far from shore. While the deposition of terrigenous sediment was in progress near the land, other phases of sedimentation were in progress farther from it, where wind-blown dust, and shells and skeletons of marine animals and plants, were accumulating.

Since the land areas of the Ordovician period were of various sizes, of various sorts of rock, and presumably of various heights, conditions apparently existed for the deposition of all sorts of sediments about their borders. The conditions which determined variations in the sediment also influenced the rate of sedimentation. The accumulation was doubtless more rapid along the borders of such a land mass as that in the eastern part of the United States, than about the smaller islands at various points farther west, and sediments must have gathered more rapidly on that side of any land mass towards which the larger part of its drainage was directed, than on the other.

The sediments deposited during the Ordovician period are in keeping with these general principles. Adjacent to the broad but not deep arm of the ocean which covered the larger part of the Mississippi basin (Fig. 129) there appears to have been no source of abundant sediments. Along the western base of the elongate tract of land (Appalachia) in the eastern part of the United States, mud, sand, and gravel, washed down from the land, were being deposited. In general the coarser materials were left nearer the land, while the finer were carried farther out. Alternating beds of coarse and fine sediment may indicate either that the adjoining land was higher at some times than at others, or that the climatic conditions or the vegetal covering changed, or that waves and currents varied in their strength. Along this belt, where the Appalachian mountain system was to appear later, limestone, the product of clear waters, is very subordinate to clastic rocks among the formations of the Ordovician system. Concerning the formations made along the eastern border of Appalachia, little is known. If the Ordovician shore was east of the present coast, the formations of the period are obviously not exposed; if it was west of the present coast, the sediments deposited within the present land area were either subsequently removed by erosion, or are concealed by later beds, or have been metamorphosed, for the most part, past recognition.

The beds of sediments forming at the same time in Newfoundland and in the northeastern parts of Canada were largely of limestone, indicating that abundant débris from the land was not brought to this region. Likewise in the area west of the Adirondacks, in the Ottawa basin, the prevailing sedimentation seems to have been organic rather than clastic, indicating that the land to the north was not furnishing abundant sediments to this region, either because it was low, or perhaps well clothed with vegetation, or because the drainage was in some other direction.

About the isolated land masses farther west, beds of sand and mud, subsequently to become sandstone and shale, were in process of accumulation; but the sources of material appropriate for such formations were not extensive, and the formations themselves are correspondingly limited. Here the conditions for the formation of limestone prevailed, for while shell-bearing and other lime-secreting animals and plants may have been no more abundant far from land than near it, their shells were probably more abundant *relative to the sediments derived from the land.* The occasional variations from limestone to shale or sandstone in this region were probably connected with oscillatory relations of land and sea, or currents. When the land was low, and the waters relatively free from terrigenous sediments, limestone appears to have been making; when the land was higher, more material was brought to the sea by the streams; and where the ocean water was shallow, this material was carried relatively far from the land whence it came.

But even during those intervals when the land was so low as not to yield abundant sediments, preparation was making for future formations of clastic rock. While in this attitude, the formations of the land were undergoing decay, even though the products of decay were not removed. Under these conditions, thick mantles of residual earths accumulate, representing the excess of rock decay over transportation. When, after such intervals of rock decay, uplift of the land gives the streams transportive power, they find a large amount of disintegrated material ready for removal. Under such conditions, land surfaces are rapidly degraded, and sediments rapidly accumulated about them.

Concerning the Ordovician strata of the western portion of North America much less is known, since most of the region has not been studied in detail; but it is safe to assume that the same processes, governed by the same principles, were there in operation. Ordovician strata are known in the Black Hills of South Dakota,[1] in Indian Territory,[2] Texas,[3] at various points in New Mexico, Arizona, California,[4] Utah,[5] Nevada,[4] Wyoming,[6] Montana, Colorado,[7] and British America,[8] and are doubtless present over considerable areas where now completely concealed.

Looked upon as a whole, the sediments of the Ordovician period were as wide-spread as the Ordovician seas themselves. To them, all preceding formations of rock so situated as to be subject to erosion, contributed, and their development meant the destruction of an equivalent body of older rock. The old material which entered into the new system was brought from the land by streams, worn from its shores by waves, or blown to the sea by winds; and where terrigenous sediments failed, or where they were relatively unimportant, the shells and other secretions of animals and plants accumulated, giving rise to sedimentary rocks of organic origin. Even these had their ultimate source in the older formations, for the mineral matter extracted from the sea to make the shells had been dissolved from older formations during the process of their decay, and brought to the sea in solution by the same streams which brought the mud in suspension.

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[1] Todd, Geology of South Dakota; and Jaggar, 21st Ann. Rept. U. S. Geol. Surv., Pt. III, p. 178.

[2] Taff, Atoka folio, U. S. Geol. Surv. and Professional Paper No. 31.

[3] Richardson, Bull. 9, Univ. of Texas Min. Surv., p. 32. The Ordovician is here unconformable on the Cambrian; idem., p. 27.

[4] Spurr, Bull. 208, U. S. Geol. Surv.

[5] King, Geol. Surv. of the 40th Parallel, Vol. I.

[6] Absaroka and Yellowstone folios, U. S. Geol. Surv.

[7] King, op. cit. and Anthracite-Crested Butte, Pike's Peak and Ten Mile folios, U. S. Geol. Surv.

[8] Dawson, Bull. Geol. Soc. Am., Vol. XII, p. 68.

While the rocks of the Ordovician system were as widely distributed as the Ordovician seas, their present exposures (Fig. 129) are much less extensive, for they are to be seen only where they have either never been covered by later formations, or where the beds which once overlay them have been removed by erosion. These areas, taken together, are relatively small. Elsewhere, where the Ordovician rocks exist, they are buried by later deposits, and are, for the most part, inaccessible. They are known, so far as known at all, only by inference, and by the meager data afforded by borings and excavations. But even by these imperfect means, it is known with a reasonable degree of certainty that the Ordovician system underlies much of the eastern interior of North America, though concealed by later beds. The general stratigraphic relations of the Ordovician system where the strata have not been greatly deformed are shown in Fig. 136.

It is probable that the larger part of the ocean basins was continuously submerged during the Ordovician as during earlier periods, and that in them the Ordovician strata overlie conformably those of Cambrian age. Though nothing can be known directly of the Ordovician system beneath the sea, it is important, in the conception of the system as a whole, to remember that it probably underlies most of the ocean, as well as many of the younger formations of the land, and that its exposed margin is but a trivial fraction of its total area.

Sections of the Ordovician.

New York section.—The strata of the Ordovician, like those of every other system, are divisible into series and formations, both on lithological and paleontological grounds. In North America the formations were first studied systematically in New York, and the New York section remains in some measure the standard to which others are referred. On the basis of variations in the formations themselves and in the fossils which they contain, the system in New York was early divided into five formations. Numbered in the order of their sequence, these subdivisions are as follows:

Ordovician system........	5. Hudson River formation
	4. Utica formation
	3. Trenton formation
	2. Chazy formation
	1. Calciferous formation

Most of the above names are derived from localities where the rocks representing the several epochs are exposed. It is not to be understood that these epochs were of equal duration, or that the corresponding formations are equally thick or equally distinct. The first two formations have sometimes been grouped under the name Canadian, and the last three under the name Trenton, though this grouping has little significance.

Recently it has been proposed [1] to substitute the following classification for that hitherto in use:

Champlainic [2] (Lower Silurian or Ordovician)	3. Cincinnatian (Neo-Champlainic)	Richmond beds [3] (Ohio and Indiana) Lorraine beds Utica shales
	2. Mohawkian (Meso-Champlainic)	Trenton limestone Black River limestone Lowville limestone
	1. Canadian (Paleo-Champlainic)	Chazy limestone Beekmantown limestone

With reference to this classification, it may be said that there seems no adequate reason for supplanting the term Ordovician. The subdivision of the system into three main series, a lower, a middle, and an upper, is certainly to be commended on the basis of convenience. So much of the classification is applicable universally. The subdivisions in the right-hand column above are based on the detailed work of recent years, and must be accepted as best expressing present knowledge of the system in New York. The relations of the old and the new classifications to each other are evident on inspection.

Perhaps the following may be accepted for the present as the most satisfactory compromise:

Ordovician	Upper Ordovician (or Cincinnatian)	Richmond beds (Ohio and Indiana) Lorraine beds Utica shales
	Middle Ordovician (or Mohawkian)	Trenton limestone Black River limestone Lowville limestone
	Lower Ordovician (or Canadian)	Chazy limestone Beekmantown limestone (=Calciferous)

[1] Clark and Schuchert, Science, Vol. X, 1899, p. 876; and Am. Geol., Vol. XXV. 1900, p. 118.

[2] The term Champlainic was proposed by Hall, Vanuxem, Mather, and Emmons, in 1842, to include what is now known as Ordovician and the Potsdam

[3] Winchell and Ulrich, Geol. of Minn., Vol. III, Pt. 2, p. ciii; and Nickles, Am Geol., Vol. XXXII, p. 202.

The above subdivisions of the system indicate that successive epochs of longer or shorter duration gave rise to recognizable differences in sedimentation, and that these differences in sedimentation were accompanied by faunal changes, usually not profound. The general conformity between the several formations of the system, and the conformity of the lowest with the Cambrian, shows that great geographic changes did not affect the region of New York while the Ordovician strata were in process of deposition. Locally, beds corresponding to the Chazy are wanting, but even in such areas there is only a moderate unconformity between the Beekmantown formation and the Middle Ordovician series. The land surface of the Chazy epoch, where there was land, seems therefore to have been low and subject to little erosion.

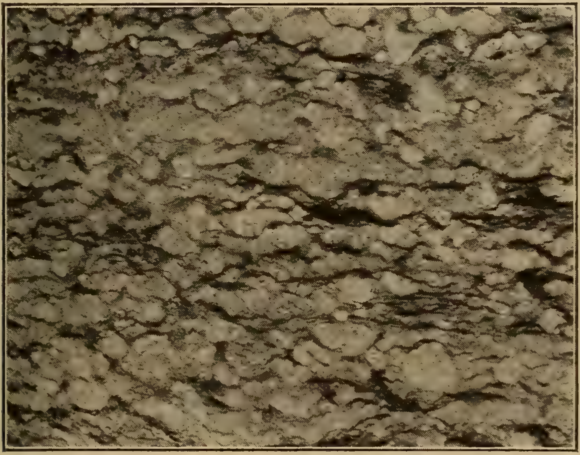

FIG. 130.—Chazy limestone. From Phelps Point, Grand Isle, Vt. Shows *Strephochetus oscellatus*.

The lowest formation in New York (the Calciferous or Beekmantown) is an impure limestone, or sometimes a calciferous sandstone. During its deposition, the general relations of land and sea remained much as in the late Cambrian. After it had attained a thickness of a few hundred feet, change of relations affected much of the Appalachian trough, converting into land considerable areas which had been submerged. After these disturbances had taken place, the only part of New York known to have remained under water is an area in the extreme northeastern part of the state, to which a bay from the Atlantic reached. In this bay the sediments of the Chazy formation were deposited.

The life of the bay, as shown by the fossils, was somewhat unlike that which had inhabited the same region during the preceding epoch. Both in the Chazy basin, and in a long narrow channel to the east (the Levis channel, extending from Newfoundland to near Albany) the fauna of this epoch had more likeness to that of Europe than to that which lived at the same time in the Mississippi basin.[1] After the Chazy limestone had attained a thickness of several hundred feet, the Chazy basin appears to have been drained, and at about the same time the sea again invaded New York, entering from the south and west, and the deposition of limestone (the Middle Ordovician) was resumed on the surface which had for a time been land. The fossils of the new formation are unlike those of the formation on which it rests. Later, the deposition of limestone gave place to the deposition of mud (Utica shale). During this epoch, connection was again made between the Atlantic and the eastern interior sea by way of the St. Lawrence valley,[1] as shown by the migration of animals from the former body of water to the latter. After the Utica formation had reached a thickness varying from a few feet in some places to a few hundred feet in others, it was buried beneath other sediments (the Hudson River or Lorraine formation) containing the relics of a somewhat different fauna. The successive changes in faunas probably indicate changes in the geographic conditions of the region though their character and extent are not definitely known. With the exception of the changes noted above, the Ordovician seems to have been, for this region, a period of general quiet, though oscillations of relative level between land and sea doubtless took place more than once during its progress.

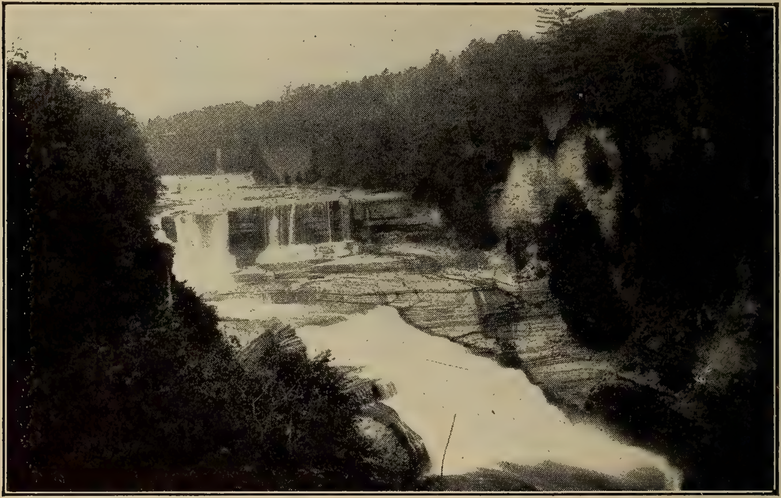

Fig. 131.—Trenton Falls, Trenton, N. Y. The locality whence the Trenton formation derived its name. (Darton, U. S. Geol. Surv.)

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[1] Ulrich and Schuchert, N. Y. State Museum, Bull. 52, pp. 633–663.

Southern Wisconsin section.—It is not to be understood that the same subdivisions hold for the Ordovician system in all regions, and even if the same number of subdivisions is made elsewhere, it does not follow that they are equivalent, severally, to those of New York.

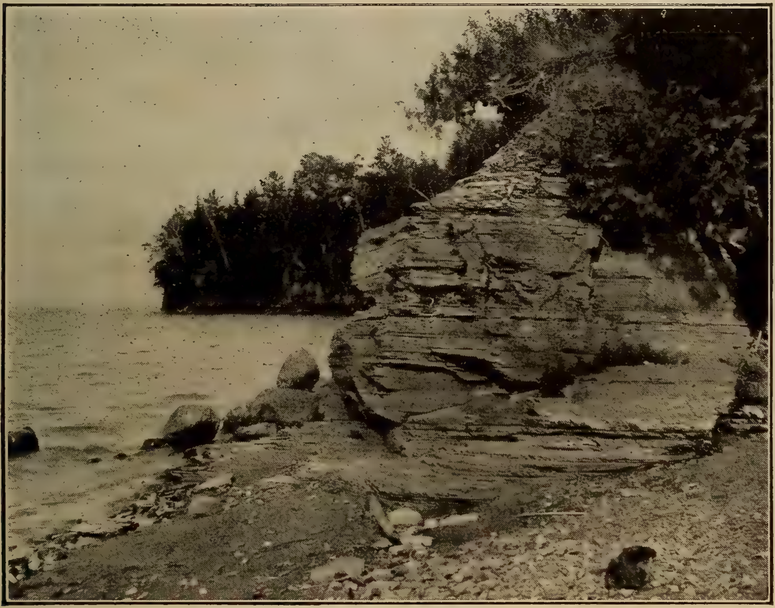

Fig. 132.—Exposure of the Utica shale. Bluff at Van Tine's, on the west shore of Grand Isle, Lake Champlain. (Perry.)

In Wisconsin, Iowa, and Minnesota, for example, the formations commonly recognized, numbered in the order of their deposition, are as follows:

Upper Ordovician........	5. Hudson River (Cincinnati) shale.
Middle Ordovician........	4. Galena limestone. 3. Trenton limestone.
Lower Ordovician........	2. St. Peters sandstone. 1. Lower Magnesian limestone.

While there is here, as in New York according to the older classification, a fivefold division of the system, it is not certain that any formation of Wisconsin is the exact equivalent of the formation which occupies the corresponding position in the New York section.

In other words, it does not follow that because the conditions for limestone formation gave place to the conditions for shale formation in New York at a particular time, similar changes took place in the interior, or in any other distant area, at the same time.

When the above names were applied to the Ordovician formations of Wisconsin, the third and fifth formations were so named on the supposition that they were the approximate equivalents of the New York formations of the same name, while the Galena limestone was regarded as a local development of the upper member of the Trenton group, in which were also included the ill-defined equivalents of the Bird's Eye (Lowville) and Black River limestones of New York.[1] Recently, question has been raised relative to the correctness of this correlation.[2] It has been urged that the formation named Trenton in the upper Mississippi basin corresponds to the Lowville and Black River beds of New York, while the Galena is the exact equivalent of the Trenton of New York. The validity of this correlation remains to be deter-

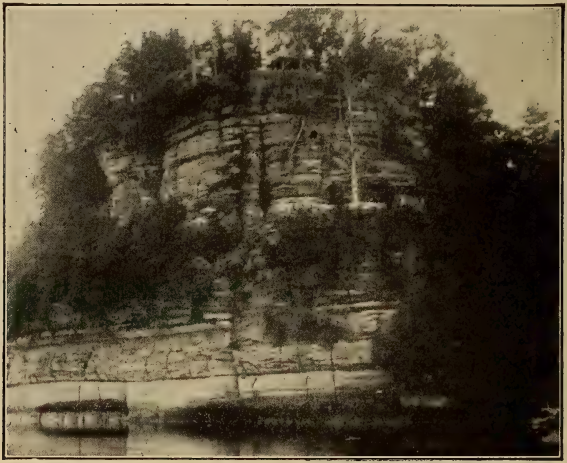

FIG. 133.—*Starved rock*, an isolated mass of St. Peters sandstone on the Illinois river near La Salle. The texture of the rock is essentially the same as at the present border of the formation, 125 miles or so farther north.

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[1] See Geol. of Ia., Hall and Whitney, Vol. I, pp. 54–70, and Geol. of Wis., Vol. I, 1862, pp. 31–55.

[2] See Ulrich and Winchell, Geol. and Nat. Hist. Surv. of Minn., Vol. III, Pt. II, pp. 83–128.

mined. As implied above, it is improbable that there is any exact equivalency between the eastern and the interior series.[1]

The classifications of New York and Wisconsin have been adapted, with but little change, to the Ordovician formations of most of the area between the Appalachian mountains and the Great plains.

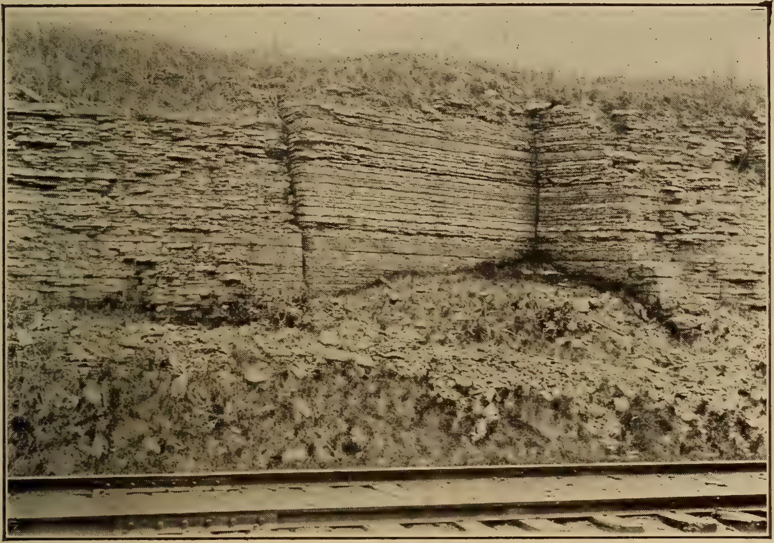

Fig. 134.—Trenton limestone near Fort Snelling, Minn. Shows two systems of joints. (Calvin.)

The Appalachian sections.[2]—In other parts of the country, the subdivisions of the system are very different. In the Appalachian mountains of Tennessee (see section in Appendix, vol. III), a series of limestone or dolomite beds (Knox, Chickamauga, Moccasin, etc.), the lowest not distinctly marked off from the Cambrian below, is followed by a series of clastic beds (Sevier shale, Bays sandstone, etc.).[1] But the limestone (the Moccasin) of one area is thought to be the equivalent of the sandstone (the Tellico) of another but a few miles away. The exact relations of these formations to those of the northwest have not been determined. If the upper part of the Knox dolomite is the equivalent of the oldest Ordovician formation of the Upper Mississippi region, it would simply mean that when the conditions of sedimentation changed in the latter region so as to stop the formation of limestone (the Lower Magnesian) and to give rise to the deposition of sand (the St. Peters), they did not change correspondingly in Tennessee, where the deposition of limestone continued. Two formations (lithologically considered) in one locality, may well be the equivalent of one in another locality. Could the strata of Wisconsin be traced uninterruptedly to Tennessee the relations might be determined, but since the strata between these localities are chiefly concealed, the relations of the formations in the two localities must remain unknown, except in so far as the fossils may reveal them.

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[1] In Wisconsin, there is an unconformity between the Lower Magnesian limestone and the St. Peters sandstone. This and other considerations raise the question whether the Lower Magnesian formation should not be classed with the Cambrian, rather than with the Ordovician.

[2] For local details in the Appalachians, see the following folios U. S. Geol. Surv.: Gadsden, Ala.; Stevenson, Ala.-Ga.-Tenn.; Ringgold and Rome, Ga.; Estillville, Ky.-Va.-Tenn.; Briceville, Chattanooga, Cleveland, Columbia, Kingston, Knoxville, Loudon, Maynardville, and Morristown, Tenn.; Bristol, Va.; Harper's Ferry, Va.-Md.-W. Va.; Monterey, Pocahontas, Staunton, and Tazewell, Va.-W. Va.; Franklin and Piedmont, W. Va.-Va. In most of these folios, the Ordovician is classed with the Silurian under the latter name. The text of the folios frequently distinguishes between the Lower Silurian (Ordovician) and the Upper Silurian (Silurian). See also the geological reports of Alabama (especially Hayes's Rept. 1892), Georgia, Tennessee, Kentucky, and Pennsylvania (especially Summary of Final Rept., Vol. I).

It seems not improbable that the change from calcareous to clastic sedimentation in the southern Appalachian region took place at the end of the Middle Ordovician time. In the early part of the Ordovician, when similar changes occurred elsewhere, a bay opening southward to the ocean is thought to have occupied the south end of the Appalachian synclinorium, and to have been shut off from the interior sea. For this region a two-fold division of the system, a lower and an upper, seems quite as appropriate as a three-fold division. The subdivisions of the system are different in other parts of eastern America, and different names are applied to them.

In central Tennessee, the Ordovician is made up chiefly of limestone which is sometimes phosphatic. There are here several unconformities in the system, indicating that shallow water and land conditions alternated.[2]

The following sections in the Appalachian province, giving both Ordovician and Silurian formations, supplement those of the Appendix.

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[1] The subdivisions here mentioned are those of the Maynardville, Tenn., folio U. S. Geol. Surv.

[2] Hayes and Ulrich, Columbia, Tenn., folio, U. S. Geol. Surv

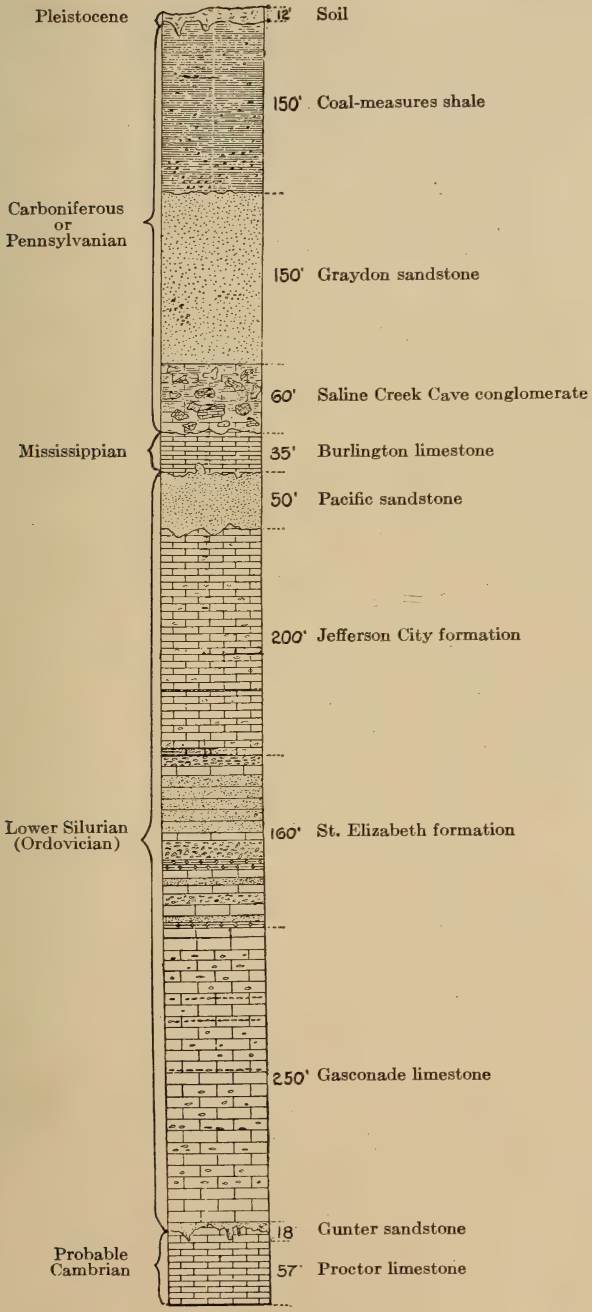

Fig. 135.—A generalized section for Miller County, Missouri. Unconformities are shown between the Cambrian and Ordovician, between the Ordovician and Mississippian, and between the Mississippian and Pennsylvanian, as well as one in the Ordovician and one in the Pennsylvanian. (Buckley.)

SECTION IN NEW JERSEY.[1]

	Names of Formation.	Thickness in Feet.	Characteristics.
Silurian.	Manlius limestone	35	Thin-bedded, knotty, dark-colored limestone.
	Rondout limestone	39	Earthy and calcareous shales and limestone.
	Decker Ferry formation (Cobleskill limestone)	52	Sandstones with calcareous bands, and limestones with shaly bands.
	Bossardville limestone	100	Fine-grained, compact, bluish-gray, banded.
	Poxino Island shale	?	Buff or greenish, calcareous; irregularly bedded; layers thin.
	Medina sandstone	2305	Soft red, somewhat shaly sandstone.
	Shawangunk conglomerate	1500–1600	Coarse quartz conglomerate; pebbles usually white or yellowish, with gray or red matrix
Ordovician.	Probable unconformity		
	Hudson River slates	1165	Shales, slates, and some sandstone.
	Trenton limestone	135–150	Limestone, often conglomeratic at base and shaly above.
	Unconformity.		
	Kittatinny limestone (mainly Cambrian)	2700–3000	Dolomitic; at one locality the top of the formation contains Ordovician fossils.

SECTION IN WESTERN MARYLAND.[2]

	Names of Formations.	Thickness in Feet.	Characteristics.
Silurian.	Salina	....	Sandstones, shales, and limestones.
		700	Sandstones predominate in lower and limestones in upper portions.
	Niagara	300	Limestones with shale partings; thin sandstone beds near the top; shales predominate over limestone at the top.
	Clinton	550–600	Thin reddish and greenish-yellow shales, with sandstone beds, and in the upper part a few thin beds of limestone.
	Tuscarora	250–300	Snow-white to light-gray quartzite, frequently cross-bedded.
	Juniata	550	Dull-red sandstones and shales, interbedded irregularly; shales predominate.

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[1] Weller, Geol. Surv. of New Jersey, Report on Paleontology Vol. III, 1903, pp. 15–80.

[2] Prosser, Jour. of Geol., Vol. IX, pp. 410–415

The above section is for Allegany County. In Washington County, lower formations are exposed as follows:[1]

Ordovician.	Martinsburg.	700–1000	Black and gray calcareous and argillaceous shales, fine-grained and uniform.
	Shenandoah. . . . . (The lowest part of this formation is Cambrian.)	2500	Blue and gray limestones and dolomites, with some slates and argillaceous shales.

Strata much folded.

SECTION IN EASTERN KENTUCKY.[2]

	Names of Formations.	Thickness in Feet.	Characteristics.
Silurian.	(The upper part of this formation is Devonian)		Brown siliceous limestone at the base; light blue clay-shale and coarse yellow sandstone; brown limestone, frequently cherty.
	Panola formation.	1–70	
	Unconformity.		
Ordovician.	Richmond formation. .	300	Blue calcareous shale, with thin beds of limestone.
	Garrard sandstone. . . .	70–100	Brown, calcareous.
	Winchester limestone.	200–230	Thin-bedded, blue, crystalline, with bands of calcareous shale.
	Flanagan chert.	0–40	Thin-bedded, gray limestone and calcareous shale; nodules and bands of chert.
	Lexington limestone . .	140–160	Thin-bedded, gray; nodules of chert at base.
	Highbridge limestone.	190 +	White limestone grading downward into gray limestone and calcareous shale.

Strata nearly horizontal.

Sections in the interior.—In the interior the sections are likewise variable.[3] The sections of the Ordovician, in the general sections given in the Appendix, give some idea of the range of the system in this region. To these may be added the following:

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[1] Clark, Maryland Geol. Surv., Vol. I, pp. 179, 180.

[2] Campbell, Richmond (Ky.) folio, U. S. Geol. Surv. All the formations of this section are classed as Silurian in the folios.

[3] The following folios give detailed sections of the exposed Ordovician between the Appalachians and the Rockies: London and Richmond, Ky.; Columbia, McMinnville, Pikeville, Sewanee, and Standing Stone, Tenn.; Atoka, I. T. See also state reports of New York, Ohio, Indiana, Michigan, Illinois, Wisconsin, Minnesota, Iowa, Missouri, Kentucky, Tennessee, and Arkansas. For areas north of the United States, see the geological reports of Canada.

SECTION IN SOUTHEASTERN MINNESOTA.[1]

	Names of Formations.	Thickness in Feet.	Characteristics.
	Devonian		
Silurian.	Unconformity.		
	Niagara(?) limestone	100–150	Light-colored crystalline limestone, often porous.
	Unconformity.		
Ordovician.	Maquoketa shales (=Hudson River)	75–100	Shales; some sand, finely bedded.
	Galena limestone	75–100	Bluish or grayish, evenly bedded, varying from compact to vesicular; sometimes arenaceous and often dolomitic.
	Trenton limestone	160	Light blue or gray; non-dolomitic.
Cambrian.	St. Peter's sandstone	122	White and friable.
	Shakopee limestone	75	Irregularly bedded, cherty; concretionary and brecciated layers; heavy-bedded light buff; shaly layers.
	New Richmond sandstone	25–40	Coarse quartzose sandstone, sometimes incoherent; sometimes cemented.
	Lower Magnesian limestone	200	Yellowish, dirty-appearing limestone; heavy-bedded below; thin-bedded above; partly arenaceous.
	St. Croix (=Potsdam sandstone)		

SECTION IN CENTRAL TEXAS.[2]

	Names of Formations.	Thickness in Feet.	Characteristics.
Silurian and Ordovician	Unconformity.		
	San Saba	315±	Dolomites and chert.
	Leon	440+	Sandy shaly dolomite; siliceous magnesian limestone; brown dolomite; Burnet marble.

Strata nearly horizontal. The equivalent of the Niagara is apparently absent. Thicknesses given are incomplete.

In Arkansas the system, though largely of limestone, includes thick beds of novaculite,[3] a fine pure siliceous sandstone, from which whetstones are made. In the southwest, the Ordovician and Silurian seem not to be well differentiated. This is indicated by the sections of Texas [1] and Indian Territory.[2]

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[1] Winchell, Geol. and Nat. Hist. Surv. of Minn., Vol. I, 1872–82, p. 280, and Pl. X. Revised to agree with nomenclature of frontispiece of Vol. VI, atlas 1900–1901, Geol. and Nat. Hist. Surv. of Minn. The Shakopee, New Richmond, and Lower Magnesian formations of Minnesota correspond to the Oneota of Iowa, and to the Lower Magnesian of Wisconsin.

[2] Dumble, Geol. Surv. of Texas, 1st Ann. Rept. Pl. III.

[3] Griswold, Ark. Geol. Surv. Ann. Rept. 1890, Vol. III.

General conditions in the eastern part of the continent.—It is worthy of note that in mid-Ordovician time, limestone was forming over a very wide area in the eastern part of North America, namely, from New England on the east to Georgian Bay on the northwest, Indian Territory and Texas on the southwest, and Alabama on the south. Limestone appears to have been forming in the Great Basin region of the west at the same time. At no previous epoch in geological history, so far as now known, was there anything like so wide-spread deposition of limestone within the limits of North America. This is to be accounted for by the fact that the sea occupied a large part of the continent, that such lands as existed were low, and that drainage from them brought little sediment to the sea. Meanwhile the forms of life which secrete lime carbonate were depositing their shells widely over the bottom of the interior epicontinental sea.

It is perhaps equally worthy of note that in the latter part of this period mud (now shale) was deposited over an almost equally extensive area extending from New York southwest to Alabama and northwest to Manitoba and beyond.

The inauguration of the epoch of clastic sedimentation may have been brought about by movements which increased the capacity of the ocean basins, thereby drawing off the waters, attended by gentle warpings which resulted, among other changes, in the uplift of an area about Cincinnati [3] (the Cincinnati arch) and the closing of the southern outlet of the bay which occupied the south end of the Appalachian synclinorium. It appears to have been about the same time (Utica epoch) that subsidence to the northeast reëstablished connection between the Atlantic and the interior sea by way of the St. Lawrence valley. It seems not unreasonable that these geographic changes should have been attended by an increase in clastic sedimentation. The wide-spread late Ordovician shale formation may mean either that the land areas were so far elevated as to allow the streams to carry a larger body of sediment to the sea, or that conditions favored the transportation of the mud farther from the shores than formerly. The fineness of the sediment would seem to indicate that the streams were rather sluggish, though locally the sediments were coarse. Associated with the Upper Ordovician shales, there are considerable bodies of limestone in some places, and of sandstone in others.

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[1] Geol. Surv. of Texas, Second Ann. Rept., p. 565.

[2] Taff, Atoka (I. T.) folio, U. S. Geol. Surv.

[3] Ulrich and Schuchert, op. cit. p. 645. The time of the origin of the Cincinnati arch has never been fixed with certainty. Hayes and Ulrich place its inception still earlier in the Ordovician. See Columbia (Tenn.) folio, U. S. Geol. Surv. The region was probably subject to disturbances at various times.

It is perhaps worthy of note that all the Ordovician formations of the interior and the east, unless it be the oldest, bear within themselves distinct evidence of shallow water origin, and even the excepted formation contains no evidence that it was laid down in deep water. Its paucity of fossils has led to the conjecture that its material may have been largely precipitated from solution.

Western sections.—In the Great Plains, the Ordovician system appears at the surface but rarely, though it probably underlies the younger formations. West of the Great Plains, the Ordovician sections, so far as now known, are simpler than in the interior or the east. In some places the whole system seems to be represented by a part of a single formation of limestone. Thus in Nevada[1] a part of the Pogonip formation seems to be the only representative of the period. Limestone was probably in process of formation in other parts of the Great Basin and in western Colorado[2] at the same time. In the Rockies sand was the principal deposit in some places[3] and limestone in others.[4] The sections of the Ordovician in the Appendix, vol. III, give some conception of its range in the west.[5]

Igneous rocks.—Igneous rocks of Ordovician age attain little importance in North America. Their general absence is in harmony with the general quiet which characterized the period. Igneous rocks of limited extent, which may date from the close of the Ordovician, are found at a few places in New York (notably Cortland County).

GENERAL CONDITIONS AND RELATIONS OF THE ORDOVICIAN SYSTEM.

Position of beds.—It has already been indicated that the Ordovician rocks are in general conformable on the Cambrian, and from

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[1] King, Geology of the 40th Parallel, Vol. I. For notes on the formations of Nevada south of the 40th Parallel, see Spurr, Bull. 208, U. S. Geol. Surv.

[2] Anthracite-Crested Butte and Ten Mile (Colo.) folios, U. S. Geol. Surv.

[3] Pike's Peak (Colo.) folio, U. S. Geol. Surv.

[4] Absaroka and Yellowstone National Park (Wyo.) folios, U. S. Geol. Surv.

[5] In addition to reports and folios already mentioned, the Ordovician (Silurian) system is shown on the Lassens Peak (Cal.) folio, U. S. Geol. Surv.

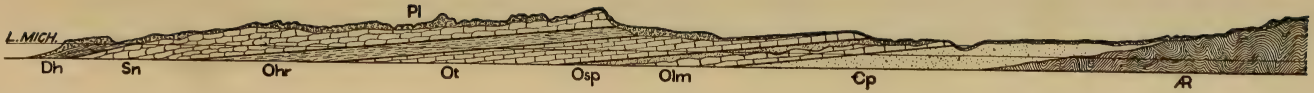

FIG. 136.—Section of the formations in southern Wisconsin, showing the position of the beds and the relations of the several systems to one another. The section extends from the Archean area, in the north-central part of the state, to Lake Michigan, in the vicinity of Milwaukee. *Æ*, Archean; *Ꞓp*, Potsdam sandstone (Cambrian); *Olm*, Lower Magnesian limestone; *Osp*, St. Peter's sandstone; *Ot*, Trenton and Galena limestone; *Ohr*, Hudson River shales. The last four formations are Ordovician. *Sn*, Niagara limestone (Silurian); *Dh*, Hamilton limestone (Devonian), and *Pl*, glacial drift (Pleistocene). The structure shown by the section is the structure characteristic of the Ordovician in much of the interior. Length of section, about 135 miles. (Chamberlin, Wis. Geol. Surv.)

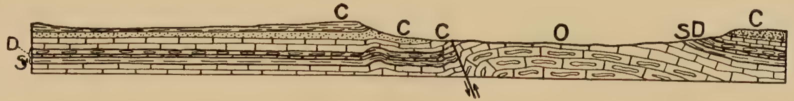

FIG. 137.—Section showing the relation of the Ordovician to Silurian, Devonian, and Carboniferous beds in eastern Tennessee. The removal of the top of a gentle fold by erosion has exposed the Ordovician. A fault on one side has concealed the Silurian and Devonian so that the Carboniferous appears next the Ordovician. *O* = Ordovician; *S* = Silurian; *D* = Devonian; *C* = Carboniferous. Length of section, about 7½ miles. The Ordovician and Silurian are combined in the original. (Hayes, Pikeville (Tenn.) folio, U. S. Geol. Surv.)

the principles which have heretofore been set forth, it is clear that they must rest unconformably on formations older than the Cambrian, where such formations constitute their substratum.

As originally deposited, the Ordovician beds probably dipped away from such lands as then existed. Thus on the south side of the land of northern Wisconsin (Fig. 136), the Ordovician sediments must have dipped slightly to the south, and on the east and west sides, to the east and west respectively. The same relations must have held originally about the Adirondacks, and about every other land area from the borders of which the sea-bottom declined. Over great areas in the interior,[1] this original and simple plan of stratigraphy has been but little modified.

In other regions, deformation of the strata subsequent to their deposition has completely changed their position. Thus in the Appalachian mountains, where the sediments were derived principally from the land to the east, and where the beds doubtless had a slight dip to the west at the time of their deposition, they now dip in various directions and at various angles, some of them being nearly vertical. Faulting has complicated their relations still further (Figs. 137, 138, and 139).[2] The same is true of the formations of the system along the eastern border of New York and the western borders of the states adjacent on the east.[3] The strata are in similar positions in some parts of Arkansas[4] (Fig. 140), Indian Territory,[5] Oklahoma, and in various mountain ranges of the Cordilleran system.[6] Even where the beds are not folded, they are sometimes affected by faulting.

Present condition of the formations.—Aside from the changes in position which the Ordovician beds have suffered, as noted above, the sediments as originally deposited have undergone more or less alteration. In some cases the change has been slight, and in others great. Many of the beds of sand and mud have been simply compacted and cemented; indeed the greater part of the Ordovician sands are still

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[1] See footnote, p. 319.

[2] For references, see p. 315.

[3] Walcott, The Taconic system of Emmons, etc., Am. Jour. Sci., Vol. XXXV, 1888. Also Merrill, New York City folio, U. S. Geol. Surv.

[4] Geological Reports of Arkansas, especially reports of 1890, Vols. I (Penrose) and IV (Hopkins).

[5] See references on p. 319.

[6] See references on p. 318.

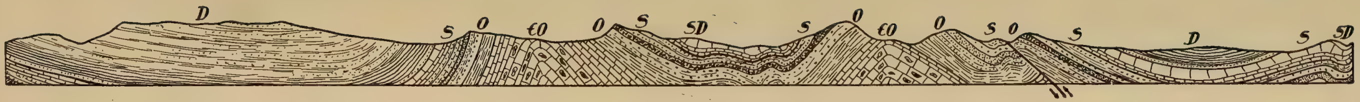

FIG. 138.—Section showing the relations of Ordovician and other beds at a point in West Virginia. *ꞒO*=Cambro-Ordovician; *O*=Ordovician; *S*=Silurian; *SD*=Siluro-Devonian; *D*=Devonian. Length of section, 18 miles. (Darton, Monterey (W. Va.) folio, U. S. Geol. Surv.)

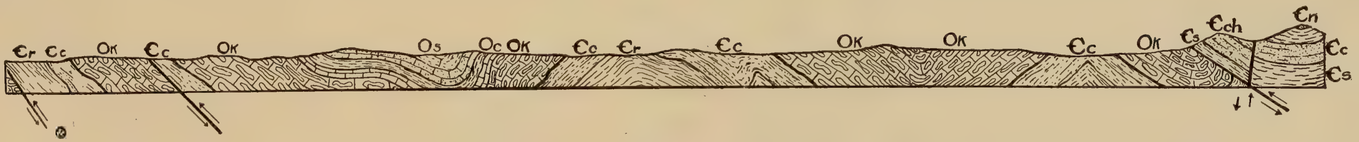

FIG. 139.—Section showing the position and relations of Ordovician, *O*, and other beds in the mountains of eastern Tennessee. *Ꞓs*, Sandsuck shale; ***Ꞓch***, Cochran conglomerate; *Ꞓn*, Nichols shale; *Ꞓr*, Rome formation, and *Ꞓc*, Connesauga shale, are Cambrian formations. *Ok*, Knox dolomite, the lower part of which is Cambrian. *Oc*, Chickamauga limestone, and *Os*, Sevier shale, are Ordovician. (Hayes, Cleveland (Tenn.) folio, U. S. Geol. Surv.)

in the condition of sandstone, and the greater part of the mud in the condition of shale, and most of the limestone is still essentially non-metamorphic. This is true over the great interior, but where dynamic action has been great, and where the original position of the strata has been greatly changed, the changes in the rock have also been great.[1] Thus in the Taconic mountains of New York, Vermont, and Massachusetts, the limestone is mainly in the condition of marble, the sandstone and quartzite have been largely changed to quartz schist and the shales to slate and schist. The same is true in some other parts of New England, and at various points in the Appalachians south of New York.

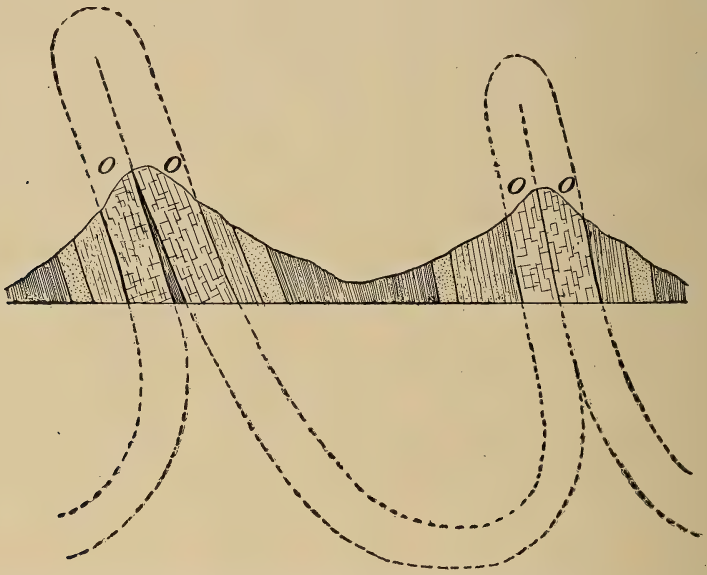

FIG. 140.—Section showing the position and relations of the Ordovician beds in the mountains of Arkansas. Length of section, about 1⅓ miles. (Penrose, Ark. Geol. Surv.)

Exposure of the Ordovician rocks.—Theoretically, the Ordovician rocks, like those of other systems, may be found at the surface where they were never buried, and where any cover they once possessed has been worn away. The areas where they have never been buried fall into two categories: First, the elevation of a land-mass about which Ordovician sediments had gathered would have given the land composed of pre-Ordovician formations a border covered by Ordovician sediments, which might never have been submerged and buried (see Fig. 141); and second, any part of the Ordovician sea-bottom distant from preëxistent land might have been raised to the estate of land at the close of the Ordovician period. If never covered by younger beds, it would belong in the category here specified (Fig. 142).

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[1] See New York City (N. Y.), Holyoke (Mass.-Conn.), and Hawley (Mass.) folios, U. S. Geol. Surv.

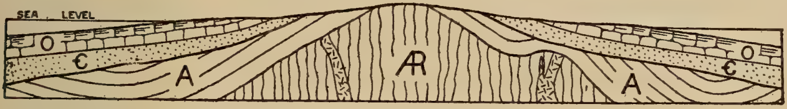

Fig. 141.—Diagram illustrating the exposure of Ordovician beds about a center of older rock. The diagram illustrates exposure of the Ordovician beds by emergence after the Ordovician period.

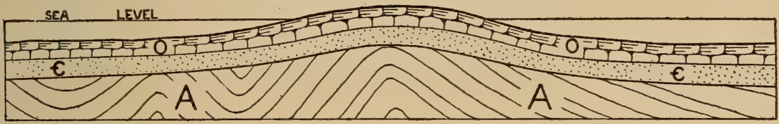

Fig. 142.—Diagram illustrating the exposure of Ordovician beds in a region where older formations do not appear at the surface. The exposure results from emergence.

The situations where the exposed Ordovician strata were once covered, but subsequently laid bare by the removal of the overlying beds, likewise fall into two categories corresponding in some sense to those just mentioned. About the land areas of the Ordovician period, the water was presumably shallow, and here a given amount of lowering of the sea-surface relative to land would be more likely than elsewhere to bring the beds covering the Ordovician into such a position as to permit of their removal. This is illustrated by Fig. 143,

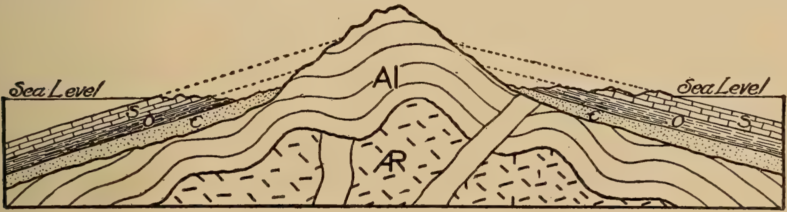

Fig. 143.—Diagram illustrating the exposure of Ordovician beds in an area where they were once concealed by younger beds, *S*, in a region where the younger beds are grouped about a center of older rock.

which represents the Silurian strata, *S*, as once covering the Ordovician, *O*; but the removal of the former has exposed the latter. Again, if any part of the sea-bottom not immediately associated with a pre-existing land area were lifted above its surroundings, not at the close of the Ordovician, but at some later time, the uppermost strata would be in a position favorable for removal. With their removal, the Ordovician beds beneath would be discovered (see Fig. 144). In the cases illustrated by Figs. 141 and 143, the Ordovician outcrops would appear around or against the outcrops of older formations; in the cases represented by Figs. 142 and 144, the Ordovician system would itself be the center about which younger beds outcrop.

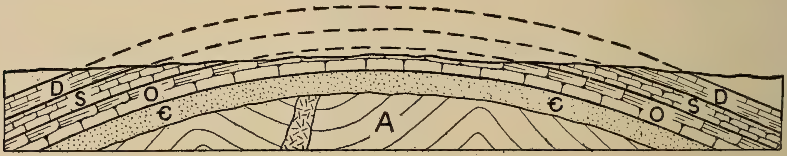

Fig. 144.—Diagram illustrating the exposure of Ordovician beds where they have been discovered by erosion in a region where older formations do not appear at the surface.

The map (Fig. 129) shows the principal areas where the Ordovician strata appear at the surface, and the relations of their outcrops to pre-Ordovician lands (compare Figs. 38 and 95). From this map it is seen that outcrops of Ordovician are found along the western border of Appalachia; in Wisconsin, South Dakota, Missouri, Texas, and several States farther west, and also at many points north of the United States. In most of these situations the outcrops of the Ordovician are adjacent to exposures of Cambrian or pre-Cambrian formations. Where the outcrops of the Ordovician strata are next a pre-Cambrian formation, rather than next the Cambrian, it means that the margin of the Ordovician sea extended landward farther than the Cambrian for that locality, and the deposits of the later period lapped over and buried those of the earlier. In the vicinity of Cincinnati, in Ohio, and adjacent States, the Ordovician strata appear at the surface in an area where older formations are not seen. The relations are shown by Fig. 145.

If the attempt be made to refer the individual outcrops of the Ordovician strata to one of the categories already mentioned, difficulty is at once encountered, for it is not always possible to say how

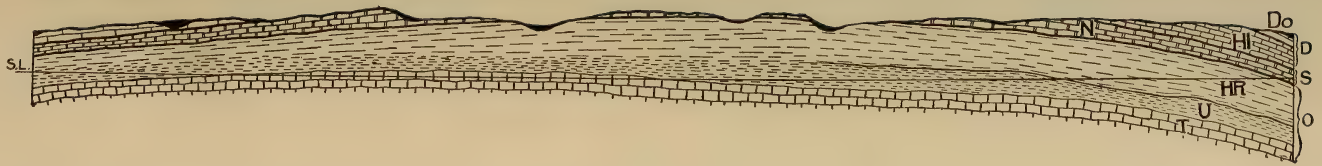

FIG. 145.—Section across the Cincinnati arch illustrating the principles shown in the preceding figure. *O*, Ordovician; *S*, Silurian; *D*, Devonian. Of the Ordovician beds, *T*=Trenton; *U*=Utica; *HR*=Hudson River. Of the Silurian beds, *N* represents Niagara. Of the Devonian beds, *Hl*=Helderberg, and *Do*=Onondaga (Corniferous). *SL*=Sea-level. Length of section, about 160 miles. (Eighth Ann. Rept., U. S. Geol. Surv.)

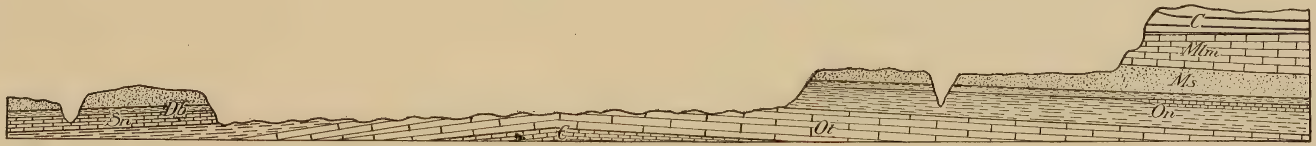

FIG. 146.—Section through the central valley of Tennessee, from Harpeth River to the top of the Cumberland plateau. Illustrates the exposure of Ordovician beds as the result of removal of overlying strata. *Ꞓ*,=Cambrian; *Ot*=Trenton limestone, and *On*=Nashville shale (Ordovician); *Sn*=Niagara limestone (Silurian); *Db*=Berea shale (Devonian); *Ms*=sandstone, and *Mlm*=Mountain limestone (Mississippian or Lower Carboniferous); *C*=Coal Measures. Length of section, about 120 miles. (Safford, Geol. of Tennessee.)

far their exposure is due to the subsequent removal of beds which once overlay them. It is barely possible that in the Taconic region of western New England and eastern New York, Ordovician beds are exposed which were never covered, except by glacial drift. Some portions of the exposed Ordovician in New York, Wisconsin, and other States may possibly never have been buried beneath marine deposits of later age, though this can hardly be affirmed. It was formerly thought that the Ordovician beds of southwestern Ohio and adjacent parts of Indiana and Kentucky were arched up at the close of the Ordovician to such an extent as to give rise to an island which was never afterward covered by the sea; but it now appears that the final emergence of the "arch" occurred at a later time. The extensive exposure of the Ordovician formations in this region was therefore probably brought about by the removal of the younger beds which once overlay them (Fig. 145). The same is true of the Ordovician outcrops in central Tennessee (Fig. 146). In the Appalachian system, the exposures of the Ordovician beds are almost wholly due to the removal of the strata which once overlay them. The outcrops along the Ouachita uplift in Arkansas, and most of those farther west, probably fall into the same category.

The Ordovician formations are wanting in some regions where their presence might have been expected. Thus in the Black Hills of South Dakota, where, it will be remembered, there is an area of Proterozoic rock surrounded by a border of Cambrian, Ordovician strata are known to be exposed at but few points. Theoretically there might have been a belt of Ordovician rocks surrounding the Cambrian, just as the Cambrian surrounds the core of older rock. The Ordovician system as well as the Upper Cambrian probably once covered the Black Hills area. Where the system is not exposed about the Cambrian, the Ordovician strata were probably removed by erosion during some post-Ordovician period when the region was above sea-level. When the region was again submerged, new deposits probably covered all the Ordovician strata which had escaped destruction (Fig. 147). These later beds have been removed so as to discover the Ordovician at but few points.

Thickness.—From what has been said it is easy to infer that the thickness of the Ordovician system varies greatly (see p. 248). In the Appalachian mountains it is to be measured by thousands of feet, while in the interior it is to be measured by hundreds instead (see sections pp. 318–320). In Wisconsin and Iowa, where the system seems to be full, that is, where sedimentation seems to have been continuous from the beginning of the period to its end, the aggregate thickness is somewhat less than 1000 feet.

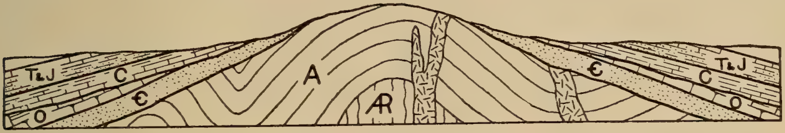

FIG. 147.—Diagram illustrating one cause of the failure of Ordovician beds to appear about a center of older rock.

Width and position of outcrops.—The relation between the thickness of a rock system and the width of the belt where it appears at the surface has already been set forth in connection with the Cambrian. The same principles are applicable here. In the interior, where the system is relatively thin, it sometimes appears at the surface in relatively wide belts or areas (Fig. 129), while in the eastern mountains, where it is thick, it appears at the surface in a succession of narrow and parallel belts.

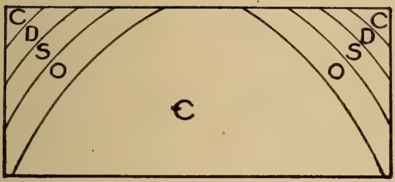

FIG. 148.

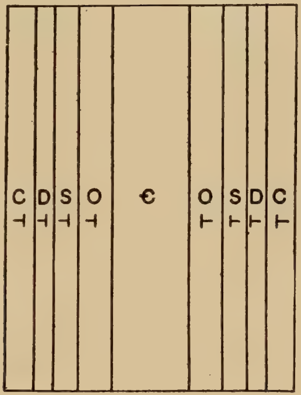

FIG. 149.

FIG. 148.—Diagram illustrating the double outcrop which the Ordovician, *O*, should show in a truncated anticline where erosion has cut down to older formations. The two outcrops should appear on opposite sides of the axis of the anticline.

FIG. 149.—Ground plan illustrating the structure shown in the last figure. The Cambrian system, *Є*, is flanked on either side by the Ordovician system, *O*, and this in turn by the Silurian, *S*, Devonian, *D*, and Carboniferous, *C*. The figure also shows the direction of the dip of the beds.

If erosion has cut off a fold down to the proper level, there should be, on either limb of the anticline involving the Ordovician strata, a belt where that system appears at the surface (Figs. 148 and 149); but faults have in some cases had the effect of concealing the beds which might otherwise have come to the surface on one or both sides of a truncated fold. Thus the outcrops shown in Fig. 150 would result from the faulting shown in Fig. 151. Faulting may likewise affect the outcrop in regions where the strata are not deformed, but faulting is less common in such regions. The principle involved is illustrated by Fig. 152.

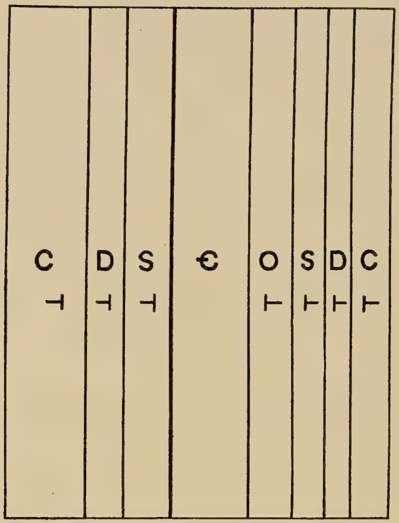

FIG. 150.

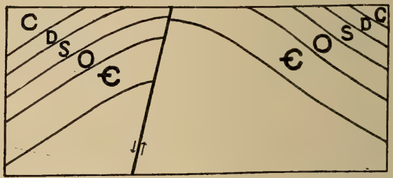

FIG. 151.

FIG. 150.—Ground-plan diagram, illustrating the failure of one system of rocks, *O*, to appear on one side of the anticline.

FIG. 151.—Cross-section showing the structure illustrated by the preceding figure. On one side of the axis of the anticline, *Ꞓ*, *O*, *S*, *D*, and *C* appear in succession. On the other side, *O* does not appear.

CLOSE OF THE ORDOVICIAN PERIOD.

The close of the Ordovician period was marked by geographic changes of more importance than those which took place at its beginning or during its progress. These changes were the result of deformative movements whose cause is not fully demonstrated, but which may perhaps have been due to the shrinking of the earth, involving the sinking of the ocean bottoms and the draining off of the epicontinental waters to a large extent, attended by some slight deformation of the general surface of the continents and some notable flexure of special tracts. The withdrawal of the waters appears to have converted extensive stretches of Ordovician epicontinental sea-bottom into land. The land area of the Lake Superior region (Fig. 129) was greatly enlarged. From it land probably extended, via Missouri,[1] as far south as Texas, and perhaps beyond. It may have extended as far west as the Rocky mountains, and east to the Cincinnati arch. If this be true, a great expanse of land, the surface of which consisted of Ordovician strata, came into existence at this time in the very heart of the continent. The elevation of this land must have been slight, for it seems to have suffered little erosion before most of it was again submerged and covered by sediments of lesser age. It is indeed the wide-spread absence of the lower part of the Silurian system (the Oswegan series, p. 370), rather than pronounced stratigraphic unconformity between the Ordovician and the Silurian of the interior, which indicates the extensive emergence of land referred to. There is, however, an unconformity between the Ordovician and Silurian systems, in some places, as in Iowa,[2] Arkansas,[3] and Tennessee,[4] and the Devonian or later beds sometimes rest on the Ordovician, with no Silurian between. Throughout much of the western part of the continent also, the land seems to have emerged at about this time, for the Silurian system is wanting in many regions where the Ordovician is present.[5]

The folding movements were less wide-spread. The most considerable was in western New England and eastern New York, in the region of the Taconic mountains. Here both the Cambrian and Ordovician systems were thick, and at this time they were folded and lifted above the seas beneath which they had accumulated. Under the influence of the intense dynamic action involved in the folding, the rocks were

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[1] The pre-Cambrian area of Missouri is often referred to as an island at this time. It has been urged, however, that the Cambrian, Ordovician, Devonian, and Carboniferous beds once overlay it. See Keyes, Science, Vol. VII, p. 388, 1898, and Bull. Geol. Soc. Am., Vol. XIII, pp. 268–292.

[2] See Silurian, pp. 371–378.

[3] Williams, Am. Jour. Sci., Vol. 48, 1894, p. 325.

[4] Pp. 371–378.

[5] See sections of Appendix, Vol. III.

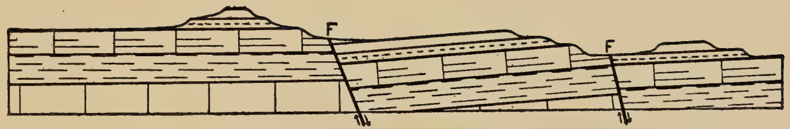

Fig. 152.—Diagram illustrating the effect of faulting, where there is no folding, on outcrops. (Hayes, Bull. 4, Geol. Surv. of Alabama.)

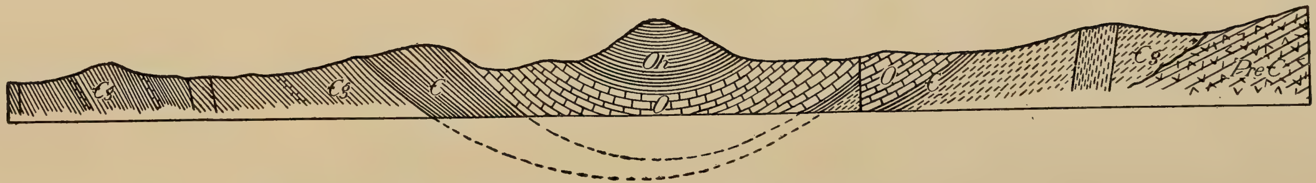

Fig. 153.—Diagram showing the structure of Ordovician and associated formations in the Taconic mountains. Pre-Ꞓ, Pre-Cambrian formations; *Ꞓg*, slates with interbedded limestone and sandstones of the Georgian (Lower Cambrian) terrane; Ꞓ, Cambrian hydro-micaceous (Potsdam) shales; *O*, Trenton, Chazy, and other limestones of Ordovician age; *Oh*, Hudson (hydro-micaceous) shales. (Walcott.)

metamorphosed, and the eroded remnants of the folds often show a complicated structure (Fig. 153). The orogenic disturbance may have extended south of New England, but its limit in this direction is undetermined.

About the borders of the mountain region, the Upper Ordovician shale is overlain unconformably by rocks of Silurian age, showing that the period of upturning and metamorphism followed the deposition of the youngest of the Ordovician formations, and preceded the deposition of the oldest formation which overlies the metamorphosed rocks unconformably. Thus the date of the upturning is, within limits, determined. The Silurian strata which overlie the Upper Ordovician do not belong to the first epoch of the period, so that in this region, there is an interval unrepresented by sedimentary formations.

The formations involved in the Taconic mountains were formerly known as the Taconic system. Their metamorphic character and complex structure long prevented their proper correlation. Within recent years it has been shown that the series includes the systems mentioned above.[1] It is not to be inferred that all the mountain-making movements which have affected western New England occurred at this time. Later movements, involving younger strata, affected this region, as will be noted in succeeding pages.

Between folding and the more gentle movements there are all degrees of gradation, and there were areas where only incipient folding or bowing of the strata took place. The "Cincinnati arch" and the "Nashville (or central Tennessee) dome" farther south have already been referred to. The deformation here was not great, but it appears to have been prolonged, and to have begun perhaps as early as the mid-Ordovician period. From this time on, the region seems to have been near sea-level, being now submerged and now land.[2]

Recently attention has been directed to another similar arch which may have come into existence at about the same time. This is in Arkansas,[3] Indian Territory, and Oklahoma, corresponding in position with the mountain system commonly known as the Ouachita uplift, of which it was perhaps the beginning. It has not been demonstrated that the strata of this region were deformed at this time, and if they were, the extent of the deformation has not been determined. The strata of the region were notably folded at a much later time.

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[1] Walcott, Am. Jour. Sci., Vol. 35, 1888. This paper gives bibliography (p. 30).

[2] Hayes and Ulrich, Columbia (Tenn.) folio, U. S. Geol. Surv.; also Foerste, Geol. Soc. of Am., Vol. XI, p. 604, and Vol. XIII, p. 531, Science, New Ser. Vol. X, p. 488, and 24th Ann. Rept., Dept. of Geol. and Nat. Hist. Resources of Indiana, 1899.

[3] Branner, Am. Jour. Sci., Vol. IV, 1897, p. 357. This very suggestive article has bearings on many questions besides the Ouachita uplift.

In New Brunswick and Nova Scotia there is unconformity between the Ordovician strata and those which overlie them, indicating an emergence after the deposition of the Ordovician formations, and a subsequent submergence before the deposition of the next younger strata of the region.

During the Ordovician period, as during part of the Cambrian, the eastern interior sea seems to have been connected with the Atlantic in the latitude of northern New England and the Gulf of St. Lawrence. During the disturbances which closed this period, this connection seems to have been closed.

In the preceding paragraphs, the crustal movements referred to have been mentioned as occurring at the close of the Ordovician. It would perhaps be more accurate to say that their beginning marks the beginning of the transition from the Ordovician period to the Silurian. The duration of the interval of transition was probably long.

The separation of the Cambrian system from the Ordovician is much less marked than the separation of the latter from the Silurian which follows. For this reason it has been proposed to group the Cambrian and the Ordovician periods together under the name *Eopaleozoic*, while the other periods of the Paleozoic are classed as *Neopaleozoic*.[1]

ECONOMIC PRODUCTS.

The formations of the Ordovician, especially those of the Trenton stage, constitute one of the most productive horizons of oil and gas. The Ohio [2] and eastern Indiana oil- and gas-wells have their principal source in this formation. Both the oil and the gas are believed to be products of the organic matter which was included in the rock at the time of its deposition.

The Galena and Trenton formations in Wisconsin and in the adjacent parts of Iowa and Illinois contain ores of lead and zinc,[1] mainly in the form of sulphides or carbonates. Lead ores are also found in the Ordovician (or Cambro-Ordovician) formations of southeastern Missouri,[2] and lead and zinc ores in the south-central part of the same State. In all these regions the lead and zinc ores occur (1) in cavities formed by solution, (2) as replacements of limestone, or (3) in veins.

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[1] Dana's Manual of Geology, 1895.

[2] See Orton, 8th Ann. Rept. U. S. Geol. Surv.; Phinney, 11th Ann. Rept.; also the reports of the State Geol. Surv. of Ohio and Indiana.

The manganese ore of Arkansas is associated with the Ordovician formations.[3]

The Ordovician limestones of central Tennessee locally yield phosphates, much used as fertilizers. The workable deposits have resulted from the leaching of phosphatic limestone, and the concentration of phosphatic material [4] (Fig. 154.) The metamorphic Ordovician limestones of New England and some parts of the Appalachian mountains have been extensively used for marble.

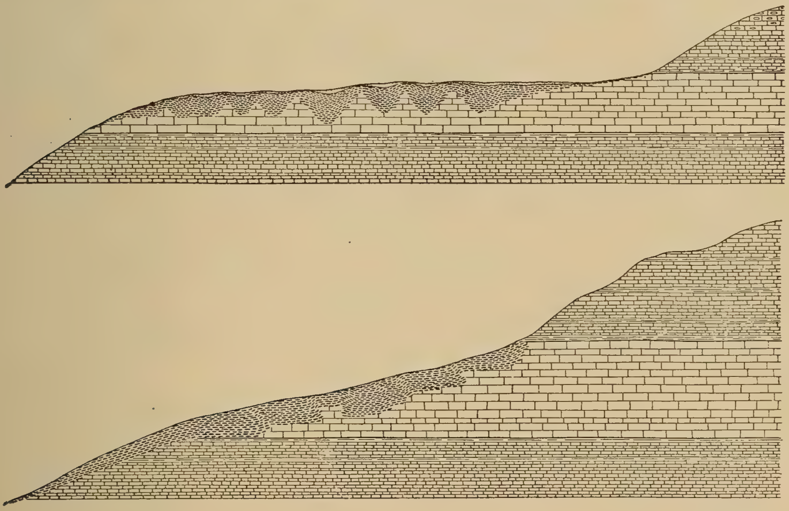

FIG. 154.—Shows the modes of occurrence of the phosphates (the shaded surface parts of the limestone) in central Tennessee. (Hayes and Ulrich, Columbia (Tenn.) folio, U. S. Geol. Surv.)

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[1] See Chamberlin, Geology of Wisconsin, Vol. IV, pp. 365–568; and Calvin and Bain, Iowa Geol. Surv., Vol. VI.

[2] Winslow, Missouri Geol. Surv., Vol. VI and VII.

[3] Penrose, Ann. Rept. Arkansas Geol. Surv., 1890, Vol I.

[4] Hayes, Columbia (Tenn.) folio, U. S. Geol. Surv.

FOREIGN ORDOVICIAN.

The Ordovician formations appear at the surface in various parts of Europe, and they exist concealed by younger formations over considerable areas where they are not seen. Fig. 155 represents the general geographic relations of land and water in Europe during this period.[1] The submerged area represents in a general way the area where the Ordovician formations are present.

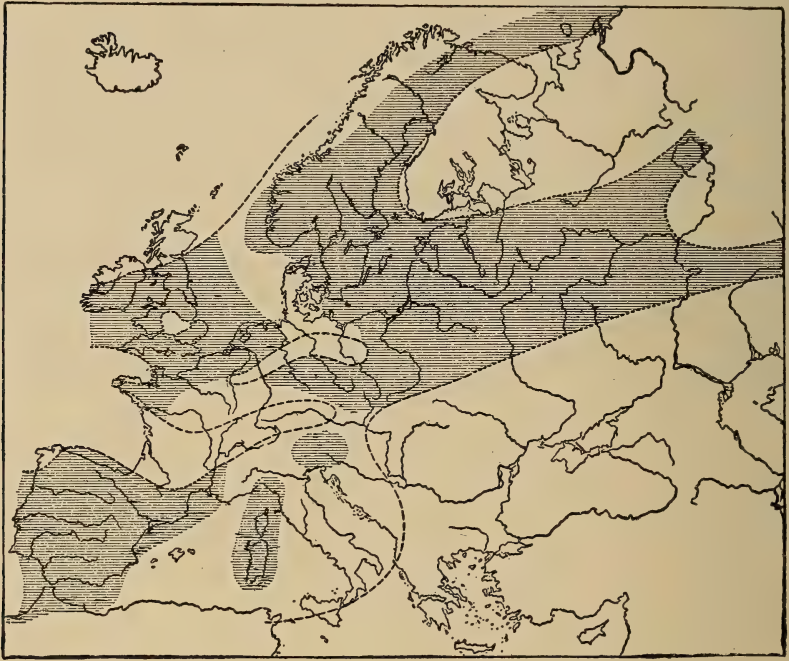

FIG. 155.—Diagram showing the relations of land and water in western Europe in the Ordovician period. The shaded parts represent areas of marine sedimentation. (After DeLapparent.)

The known formations of this system, like those of the Cambrian, are divisible into two geographic provinces, a northern and a southern. The line or belt which separates them runs from the English Channel on the west, across the plains of Germany to the heart of Russia on the east. To the northern province belong the Ordovician strata of the British Isles, Scandinavia, and Russia. To the southern belong the corresponding formations of Bohemia, southern Germany, France, Switzerland, Spain, and Portugal.

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[1] DeLapparent, Traité de Géologie, quatrième edition, p. 809.

The basis for the separation of the system into two geographic parts is found primarily in the fossils, which are notably unlike in the two provinces, and partly in the nature of the rocks themselves. The north European faunas were more closely allied to those of Asia and North and South America, and were the more general or cosmopolitan; the south European faunas were more local and provincial.[1] An illustration of the wide distribution of certain pelagic faunas is furnished by the graptolites. Of 59 species from the Skiddaw slates (Lower Ordovician) of north England, 14 are common to other parts of Britain, 25 to the Quebec group (Lower Ordovician) of Canada, and 34 to the Ordovician of Sweden.[2]

The strata of the northern province, except in the British Isles, are essentially horizontal, while those of the southern province are much more generally disturbed. Where much disturbed, they have been notably metamorphosed in both the northern and southern provinces.

In keeping with the attitude of the strata, the outcrops cover larger areas in the northern province than in the southern. The most extensive outcrop is in the Baltic region of Russia. The Ordovician beds of this region are probably continuous beneath later formations with the Ordovician of the Ural mountains, and the system probably underlies all of northern Russia.[3] Not only does the system nowhere appear at the surface over large areas in southern Europe, but there is some indication that the outcropping formations of different regions are not continuous with one another beneath younger beds.

The formations of the European Ordovician are largely fragmental, being made up of shales, sandstones, graywackes, etc., with which there is associated relatively little limestone. Where the latter occurs, it often has the form of great lenses interbedded with clastic rocks, showing that conditions favorable for its formation were not continuous over great areas. In its paucity of limestone, the Ordovician of Europe is in contrast with that of North America. The constitution of the system as a whole is such as to show that sedimentation was very varied within the area of Europe. The succession of beds is often markedly different in closely associated localities, and even the larger divisions established for the northern province do not hold for the southern.

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[1] Kayser, Geologische Formationskunde, zweite Auflage.

[2] Geikie, op. cit., p. 949.

[3] Geikie, op. cit., p. 968.

The Ordovician system was first differentiated in Great Britain, where it was described under the name of Lower Silurian,[1] a name which is still frequently applied to it. The name here used for the system, which comes from the region occupied by the Ordovices, is of relatively recent adoption.[2]

The system is represented in the British Isles by great thicknesses of strata (something like 24,000 feet maximum).[3] Locally (Wales), nearly half the system is composed of igneous rock, consisting of sheets of lava and beds of fragmental igneous rocks of various sorts. In the north of England, the successive beds of igneous rock, partly lava-flows and partly tuffs, not interstratified with aqueous sediments except near the base and summit, suggest that the eruptions took place, in part at least, on land. In Wales, on the other hand, the igneous rocks are interstratified with sedimentaries, and are therefore thought to have been ejected beneath water.[4] This is one of the most extensive, as well as one of the most ancient, volcanic tracts of Europe. Igneous rocks of Ordovician age also occur in the north of Ireland.

From north England and Wales the system thins in all directions, though it has a thickness of something like three miles in the southern highlands of Scotland. The figures given are to be looked upon as maxima, not as averages. In Scandinavia and Russia the system has but a fraction of the thickness which it possesses in Britain, and the strata are essentially horizontal. About the Gulf of Finland, some of the Ordovician beds of clay and sand are still unconsolidated. The sands and clays of the system here might be taken, so far as lithological characteristics go, for Tertiary.

In the southern province of Europe, as in most of the northern, the Ordovician system does not attain great thickness, and limestone is there more abundant than in the north. The strata are exposed about various mountains where local disturbances have upturned them, and where erosion has cut off the beds which once overlay them. Ordovician beds are not certainly known in the northern Alps, though the system may be represented by metamorphic rocks. It is present in the southern Alps. In France the system carries a bed of iron ore rarely more than six feet thick, which is commercially valuable. In its character and occurrence, it recalls the Clinton ores of the United States.[1]

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[1] Murchison, Phil. Mag. and Brit. Assoc., 1835.

[2] Lapworth, Geol. Mag., 1879, p. 13.

[3] This measurement is doubtless subject to the qualifications set forth on p. 259.

[4] Geikie, op. cit., pp. 946 and 949.

In Bohemia, though the system does not appear at the surface over a great area, it has been made classic by the paleontological work of Barrande.[2] The formation is here rich in fossils, and the faunas of few areas in any part of the earth have been studied with equal care, or with richer results. In contrast with the great abundance of fossils in Bohemia is their paucity in the corresponding formations of Germany.

Barring somewhat extensive volcanic action, the Cambrian and Ordovician periods were periods of general quiet in Europe, as in America; but at the close of the Ordovician considerable disturbances resulting in geographic changes of importance took place. Stated in other terms, it was these disturbances which brought the Ordovician to a close. These general conclusions are based on the fact that the Ordovician system of Europe is generally conformable on the Cambrian, while over considerable areas it is unconformable beneath the Silurian. This is especially true in the British Isles, where profound dynamic changes intervened. Here the stratigraphic relations of the systems show that at the close of the Ordovician, the strata which had been but recently laid down beneath the ocean were elevated, folded, crumpled, and so metamorphosed as to greatly change their character. In the Highlands of northwestern Scotland the dynamic action seems to have been exceptionally severe. Here the strata were not only folded, but the folds were overturned, and a series of nearly horizontal faults or thrust planes developed. Locally, the thrust was as much as ten miles,[3] and had for a result the burial of the Ordovician strata, sometimes without metamorphism, by the Cambrian and even the Archean rocks. Over the greater part of the

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[1] DeLapparent, Traité de Géologie, 3d ed., p. 800.

[2] Système Siluriene de la Bohème.

[3] Quart. Jour. Geol. Soc., 1884 and 1888. The latter article gives references to preceding literature on this interesting area.

European continent, on the other hand, orogenic disturbances do not appear to have taken place at the close of the Ordovician. In Europe, as in America, the great disturbances took place where thick bodies of sediment had been accumulated, or else the beds were greatly thickened by the disturbances.

The Ordovician system of Europe, like that of America, is divided into several groups of strata, but it is impossible to correlate these subdivisions with those of North America with anything like accuracy. In Great Britain the four principal divisions, beginning with the oldest, are (1) Tremadoc, (2) Arenig, (3) Llandeilo, and (4) Caradoc or Bala.

In other continents the Ordovician strata have usually not been separated from the overlying Silurian, but they are known to have a wide distribution in the Arctic regions (Kennedy Straits, Boothia, Cornwallis, Griffith, North Devon, East coast of Greenland, etc.). In south-central Siberia they are said to be represented by red beds, with salt and gypsum.[1] In northern China, the Ordovician system is represented by 3000 to 4000 feet of limestone, which overlies the Upper Cambrian conformably.

Climate.

Neither in Europe nor in America is there decisive evidence that climatic zones were distinctly marked. All that is known of the life of this era would seem to indicate that the climate was much more uniform than now throughout the areas where the strata of the period are known. The fact that the Ordovician rocks have been identified in the far north (in North Devon, the west coast of King William's Land, Boothia, etc.) by their fossils, indicates that the climatic conditions of North America and Europe must have been less diversified than now.

ORDOVICIAN LIFE.

Close sequence upon the Cambrian.—To the fact that no great physical change took place in the passage from the Cambrian to the Ordovician deposits, as usually defined,[3] is now to be added the correlative fact that there was no distinct break in the succession of life. All reasonable doubt that the continuity between the two periods was real and not merely apparent is thus removed, for had any great interval been left unrecorded by the deposits, it must have made itself manifest by a break in the continuity of the life. There seems ample warrant, therefore, for the view that the vast period from the beginning of the Cambrian to the close of the Ordovician was one long eon of progressive development and of expansion of life, and that its division into two nominal periods is artificial rather than natural.

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[1] De Lapparent, op. cit., p. 807.

[2] Blackwelder, Carnegie Institution. Unpublished evidence.

[3] Were the dividing plane placed at the unconformity above the Calciferous (Beekmantown of the east, Lower Magnesian of the Upper Mississippi Valley), an appreciable change in the life would have to be recognized, but it would not be a radical one. For North America, the plane of the unconformity appears to be the better dividing horizon.

Edaphic, Provincial, and Cosmopolitan Development.

Nevertheless, the life progress was not uniform in all regions, though in its general aspect it was cosmopolitan. It varied much as the continental evolution varied, and largely as the result of it. The variations assumed three general phases: (1) adaptation to the immediate physical environment, particularly the nature and depth of the sea-bottom (edaphic adaptation); (2) modification by self-evolution within restricted areas where isolated from other regions by barriers (provincial evolution), and (3) modification toward a universal type through the intermigration of the life of various regions when barriers were removed (cosmopolitan development).

(1) **Edaphic modification** —Areas in which the bottom was rocky, or sandy, or muddy, or calcareous, had their appropriate life, as did also the tracts of shallow and deep water, and the areas dominated by other special conditions. The assemblages adapted to these special conditions were not entirely distinct from one another, for there were not a few forms that were indifferent to these conditions, particularly the floating and free-swimming species; but the aspect of the fauna, particularly the sea-bottom portion of it, was locally modified. These modifications are well shown in the Ordovician fossils, but they are of too intricate a nature to be set forth specifically here.

(2) **Provincial modifications.**—Although for the greater part the sea was spread widely upon the face of the continent in Ordovician times, and the facilities for the intermigration and mingling of faunas were usually excellent, there is evidence of considerable separation into zoölogical provinces. This was probably due in the main to barriers interposed by gentle warpings of the sea-bottom which introduced emergent tracts and tracts of excessive depth; but probably also in

part to barriers constructed by the sea itself, in the form of shoals, bars and spits. In some cases the separation of the provinces may have been due to nothing more substantial than sea-currents and the attendant differences in temperature, or to locally increased or lessened salinity of the waters. The formation and shifting of provinces due to surface warpings seems to have been most marked in the Appalachian tract, where deformations have been more pronounced than in the interior in most geological stages. Some notable progress has recently been made in working out these provinces, but the delineations have not yet been brought to sufficient completeness and sureness to warrant an attempt to sketch them here.[1]

(3) **Cosmopolitan development.**—Notwithstanding the local and provincial modifications just named, the progress of the Ordovician life on the American continent seems to have been, on the whole, in the direction of cosmopolitanism. This was due, in part, to the wide development of the epicontinental seas, which in themselves gave a broad and rich field for evolution, and in part to the facilities for the intermingling of the faunas of the various continents. A cosmopolitan tendency is particularly marked in the great interior region which was more stable than the border tracts and which better discloses the great lines of biological movement, because less affected by the little ones.

The preceding statements relate chiefly to the shallow-water life of the sea, as this includes the larger part of all that is represented in those portions of the deposits that are now accessible. The deep-sea beds of the Ordovician are nearly all, probably quite all, inaccessible. The shallow-water life that was subject to local and regional modification embraced not only the species which were limited to particular kinds of bottom, etc., but those which were dependent on these for food and for other necessary conditions of life.

Fortunately, however, in the Ordovician deposits there is an exceptional record of the free-floating life of the ocean made by an extinct order, the *graptolites* (Fig. 167).[2] This record is not, however, isolated, as it might have been if deposited on a sub-oceanic plateau in mid-ocean, inaccessible to coast life, and covered with water too shallow for abysmal life. The graptolites are mingled more or less freely with the fossils of the shallow-water life. This implies that the open-sea life was borne freely over the epicontinental seas. This is further testimony to the sea-prevalence and the cosmopolitan tendency of the life development. Pelagic forms in general enjoy great freedom of distribution, and hence their progress is to be presumed to be much the same in all oceanic regions. Even here, absolute equality of progress is not predicable, for the ocean-currents form circuits within which they return upon themselves without compassing the whole globe, and without commingling very extensively with other waters; and hence even the floating open-sea life is assembled in some measure into vague provinces, and this has probably always been the case. But the Ordovician graptolites are found to be practically identical not only on the European and American sides of the North Atlantic, which might have been dominated by an oceanic circuit of its own, but in the seas of the times as far away as Australia, whose relations are with the Pacific, the Indian, and the Antarctic oceans. The inference is that the range of the graptolite species was ocean-wide. They were *par excellence* cosmopolitan forms. Lapworth[1] has shown that the duration of individual species was not very great, geologically speaking, and hence the succession of species was well suited to mark the contemporaneous progress of events in all quarters of the ocean. During the lifetime of the graptolites, which unfortunately was limited to the late Cambrian, Ordovician, and Silurian, Lapworth identifies a score of successive zones, each characterized by a particular species. One of these zones falls in the Cambrian, eight in the Ordovician, and eleven in the Silurian. If these be taken as chronological bench-marks, so to speak, the successive horizons of the different continents may be accurately correlated and the progress of life in the various quarters of the globe referred to a common set of standards. The succession of American faunas will claim our attention later. Our first concern is with the general progress of life.

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[1] See Paleozoic Seas and Barriers, by E. O. Ulrich and Charles Schuchert, Rept N. Y. State Paleontologist, 1901, pp. 633–658.

[2] It is not universally agreed that all graptolites were floating forms at all stages, but there seems to be little doubt that they usually were in their young stages at least.

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[1] On the geological Distribution of the Rhabdophora, Ann. Mag. Nat. Hist., 5th Ser., Vol. III, pp. 245, 445; Vol. IV, pp. 333, 418; Vol. V, pp. 45, 149, 273, and 358; Vol. VI, pp. 16, 185. On American graptolites, see particularly James Hall, Can. Org. Remains, Dec. II, 1865; 20th Rept. N. Y. State Col. of Nat. Hist., 1868; R. R. Gurley, Jour. Geol., Vol. IV, 1896, pp. 63 and 291, and R. Ruedemann, Mem. No. 7. N. State Mus.

THE GENERAL PROGRESS OF ORDOVICIAN LIFE.

While there was a fair preservation of the life of the Cambrian, there is a much superior representation of the Ordovician life. Some part of this is due to a real advance in fossilizable forms, and probably to a real multiplication of their numbers, but a part is probably also due to better conditions of preservation. The Ordovician life is probably to be regarded as the climax of the life of the first great fossiliferous period, and as such its fossils may well receive more study and fuller illustration relatively than it will be possible to give later faunas.

The Scantiness of the Record of Land Life.

Theoretically, there are strong reasons for believing that the pteridophytes and perhaps other leading groups of plants clothed the land, for they appear in abundance, in high development, and in wide differentiation in the Devonian period. The physical argument for a vegetal clothing of the land is also now stronger than before, for animal life swarmed about the shores, and limestone was sometimes laid down close to the Archean crystalline rocks and even among the granite hills, as in Ontario and elsewhere. This is difficult to understand if the crystalline rocks were naked and the wash from them unrestrained, even if their surfaces were rather low. Rather should we expect arkose sandstones in all the adjacent tract and relative scantiness of life, because the land waters would be poor in organic matter if the land bore no vegetation. If on the other hand the land were clothed with vegetation and relatively low, silty wash would be limited, the land waters rich in organic matter, and the conditions favorable at once for teeming life near the shores, and free limestone deposition as a consequence. But the record merely furnishes some imperfect relics that are interpretable as land plants, without revealing much of the land vegetation.[1]

The first record of insect life.—The oldest relic of insect life known at present is a rather obscure wing found in the graptolite shales of the Upper Ordovician of Sweden. It is referred to the order of Hemiptera (bugs, cicada, etc.). Not enough is preserved to show fully the insect's nature, but the existence of any flying insect of this order implies the presence of vegetation and of atmospheric conditions suited to active, air-breathing organisms.

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[1] Dawson, Plant Life, p. 21.

The Main Record Marine.

The marine invertebrates made up almost the whole of the recorded fauna of the Ordovician, and among these the trilobites, the cephalopods, and the brachiopods held the leading places. Of these, the brachiopods were the most numerous, the trilobites the highest in organization, and the cephalopods the most powerful. But the foreshadowings of a new dynasty were even then at hand.

The appearance of the vertebrates.—In the Ordovician near Canyon City, and at some other localities in Colorado, the remains of fish-like organisms occur in great abundance, but, unfortunately, in poor condition, associated with characteristic Ordovician invertebrates.[1] The fish relics are very fragmentary, but among them there are complete dermal plates. Rarely, a few of these plates remain joined to one another. There are also portions of the vertebral column. The relics are sufficient to make it clear that fish-like forms lived in some abundance, and that they were armed for defense. It is not equally clear that they were armed for attack.

The climax of the trilobites.—More than half of all the known genera of trilobites, as listed by Zittel, were represented in Ordovician times. Only a few of these came over from the Cambrian, while the others make their first appearance in this period. In the next period (Silurian), their numbers fell to one half, and in later periods declined still further until they disappeared at the close of the Paleozoic era. The rise and fall of the trilobites is shown graphically in the curve of the accompanying figure (Fig. 156). Their climax appears to have been reached by a rapid evolutionary ascent, and to have been followed by a more gradual decline, but the ascent was doubtless very much more prolonged in reality than appears from the record, which is doubtless less complete in the Cambrian and pre-Cambrian systems than in those of later periods. The attainment of a climax so early in the recorded history of life is a very notable event.

The cystoids and the graptolites also reach their climaxes in this period. The cystoids were, however, replaced by their near kin, the crinoids, and the much simpler organization of the graptolites makes their early climax less significant. The climax of the trilobites may therefore be regarded as the foremost great event of its kind that is definitely recorded.

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[1] Walcott, Bull. Geol. Soc. of Am., Vol. III, pp. 153–171.

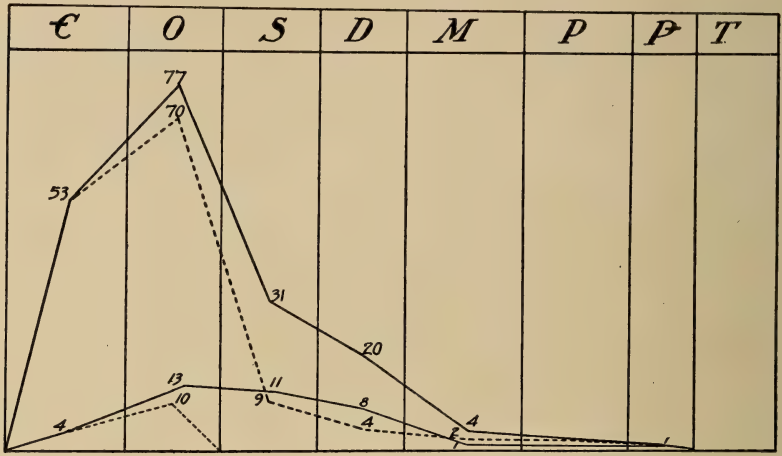

Fig. 156.—The two upper curves represent the history of the trilobites according to genera, the full line indicating the total number of genera present in the faunas of the successive periods, and the dotted line the number of new genera introduced. The two lower curves present the same data for the families of the trilobites, the full line representing the total number of families present, and the dotted line the number of new families introduced. The data for the families is taken from Beecher in the Zittel-Eastman text-book of Paleontology, Vol. I. The data for the genera is somewhat incomplete, but is as full as can be made from Zittel's "Handbuch der Palæontologie."

The general aspect of the trilobites at the high tide of their career is fairly illustrated in the group shown in Fig. 157. The Ordovician trilobites were usually much better preserved than their Cambrian predecessors, but still they are never known to have been perfectly fossilized. So general was the loss of the more fragile parts, that the nature of the appendages and of the under parts was a mooted question until recent years, when the under-structure was worked out in the case of a few forms by the skill and patience of Walcott, Beecher, and others.[1] These few forms doubtless represent the general nature of the appendages of the whole order, though notable variations are not improbable. The accompanying photograph of a model

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[1] Walcott, 28th Rept. N. Y. State Mus. Nat. Hist., 1875; Bull. Mus. Comp. Zool., Cambridge, VIII, 1881. Beecher, Am. Jour. Sci., Vol. XLVI, 1893; Vol. XLVII, 1894, and Vol. I, Ser. 4, 1896; Am. Geol., Vol. XIII, 1894, and Vol. XV, 1895. Mathew, Am. Jour. Sci., Vol. XLVI, 1893. (Weller).

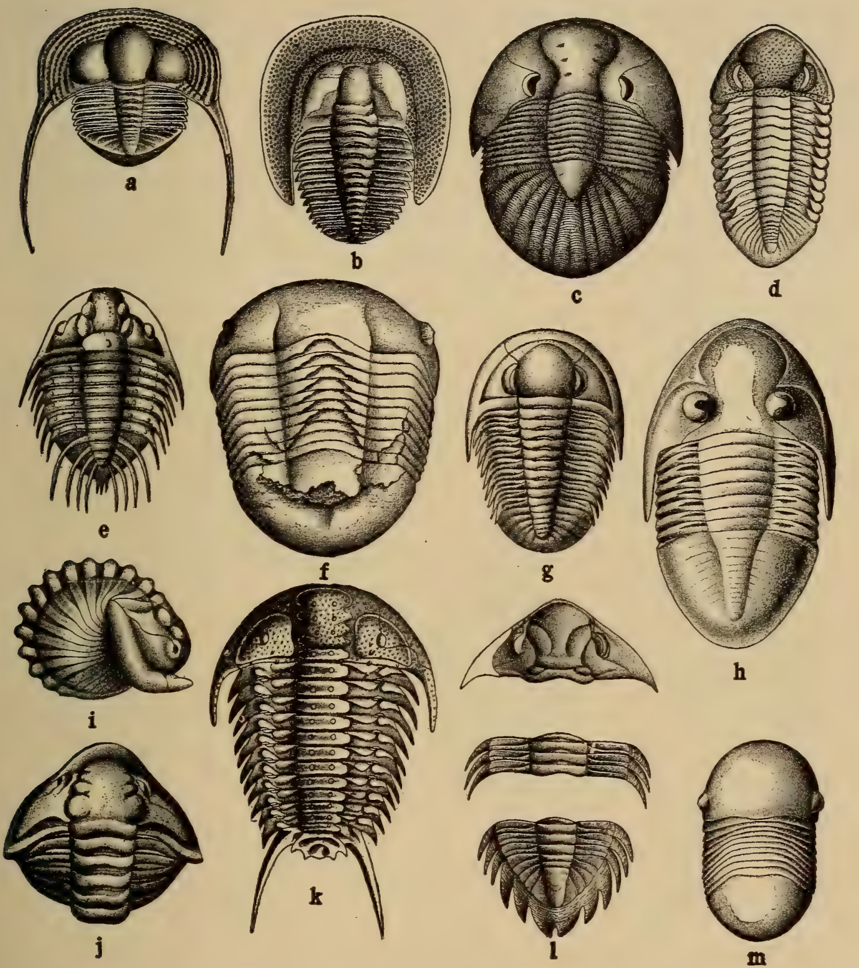

FIG. 157.—*Ordovician Trilobites.* *a*, *Trinucleus ornatus* Sternberg; *b*, *Harpes primus* Barrande; *c*, *Bronteus lunatus* Billings; *d*, *Pterygometopus callicephalus* (Hall); *e*, *Odontopleura crosotus* (Locke); *f*, *Illænus americanus* Billings; *g*, *Pröetus parviusculus* Hall; *h*, *Isotelus maximus* Locke; *i–j*, *Calymene callicephala* Green; *k*, *Ceraurus pleurexanthemus* Green; *l*, *Lichas incola* Barrande; *m*, *Bumastus trentonensis* (Emmons). The lowest order of Trilobites, the Hypoparia, are represented by figures *a* and *b*. They have no true eyes, and the facial suture is marginal or sub-marginal. Figures *e*, *f*, *g*, *h*, *l*, and *m* are examples of the trilobite order Opisthoparia, in which the posterior limb of the facial suture is directed backward, cutting the posterior margin of the head and leaving the genal angle on the free cheek. The different degrees of differentiation of the glabella should be noted. Figures *d*, *i–j*, and *k* are examples of the order Proparia which includes the highest of the trilobites; the posterior limb of the facial suture is directed laterally, leaving the genal angle upon the fixed cheek; this order was not present in the Cambrian faunas.

by Beecher (Fig. 158), made by combining parts of different individuals of *Triarthus beckii,* shows that this species possessed a row of legs extending along each side of the body and that these were furnished with fringed natatory branches. From these appendages, it is inferred that the *Triarthus* both ran and swam and was a swift active animal. It possessed antennæ, which probably signifies a well-developed tactile sense. The swimming filaments have not been found in some genera where the legs have been observed. In these cases it is noted that the legs are relatively weak, and that these are forms which had the habit of rolling up, while the *Triarthus* was stiffly articulated. The suggestion has hence been made that the trilobites followed two lines of development. The one class, being weak in power of locomotion and sluggish in habit, developed a jointed articulation and found safety when attacked in rolling up armadillo fashion, while the other acquired effective running and swimming organs and found safety in flight; but present data are insufficient to demonstrate this distinction, for the appendages of most trilobites are still unknown.

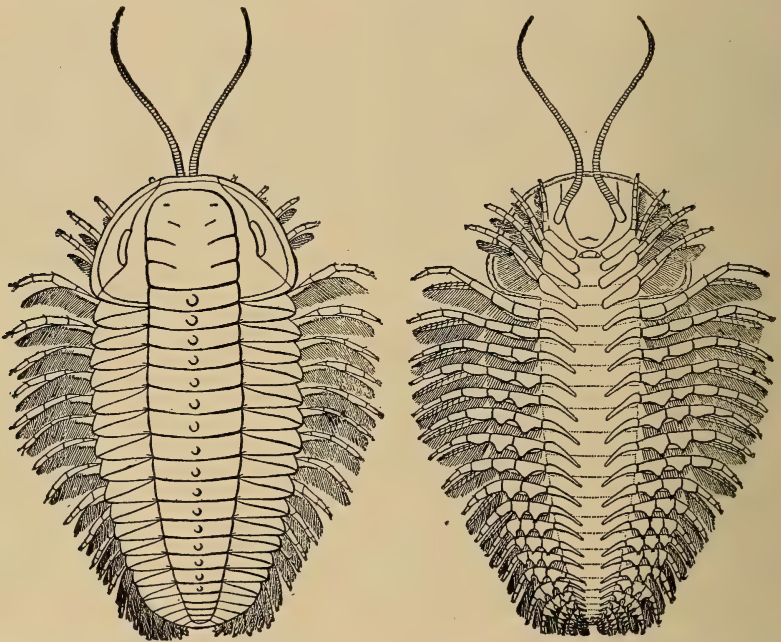

FIG. 158.—*Triarthus beckii* Green, showing the locomotive and other appendages. Dorsal and ventral aspects. (After Beecher.)

The eyes of the Ordovician trilobites, as a rule, were more prominent and better developed than those of the Cambrian forms, and showed improved adaptation by being set on a curved pedestal, so that some eyelets were directed more to the front and others more to the rear, giving an ampler angle of vision (see particularly *d* and *h*, Fig. 157). There was little or no increase in the average size of the trilobites. The *Isotelus gigas* sometimes reached a length of 18 inches and ranked among the giant trilobites, but it was equaled and even surpassed by some of the great *Paradoxides* of the Cambrian. Progress took the form of improvement of the parts and of superior adaptation rather than increased size. Curious ornamentation of the exterior was displayed in some genera, as were also eccentric departures from the simple three-lobed form, but such aberrations became far more pronounced in the early stages of the decline of the trilobites, in later periods.

Other crustaceans.—Besides the trilobites, the crustaceans were represented by a few inferior forms. Ostracodes were common in some beds (Fig. 159, *a*, *b*, *c*, *d*, *e*, *f*, *g*, and *h*) and there were a few cirripeds of which the barnacle is the most familiar modern type; but, unlike the barnacle, the Ordovician cirripeds had an elongate body and were not sessile (Fig. 159, *i*, *j*). The euripterids, a limuloid form related to the arachnids, appeared in the later part of the period.

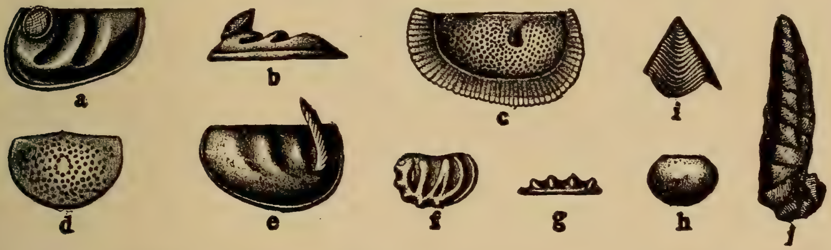

FIG. 159.—*Ordovician Crustacea*, other than Trilobites. *a–b*, *Ceratopsis oculifera* (Hall), lateral and ventral views; *c*, *Eurychilina reticulata* Ulrich; *d*, *Macronotella scofieldi* Ulrich; *e*, *Ceratopsis chambersi* (Miller); *f–g*, *Tetradella quadrilirata* H. and W., lateral and dorsal view; *h*, *Aparchites minutissimus* Hall; *i–j*, *Lepidocoleus jamesi* (Meek), a single plate and a complete individual. Figures *a–b*, *c*, *d*, *e*, *f–g*, and *h* are examples of Ordovician ostracods, all of them much magnified. Figures *i–j* are illustrations of a single plate and of the complete individual of a cirriped crustacean.

The dominance of the cephalopods.—The largest, the most powerful, and perhaps the most predaceous of the known forms of Ordovician life were the cephalopods, which seem to have come in with extraordinary suddenness. Unless the fishes, of which so little is known, contested their supremacy, they were doubtless the undisputed masters of the sea. Their relics first appear at the time of the transition from the Cambrian to the Ordovician, but they were then so far advanced in their development and so widely differentiated from allied forms as to render it probable that they had really lived much earlier. Their general aspect may be gathered from the group in Fig. 160, but only small forms, or large forms on a greatly reduced scale, are available for illustration. The dominant form, as well as the most primitive one, was the *Orthoceras* (Fig. 160, *e*), whose shell consisted of a long, straight, gently tapering cone, partitioned by plane septa into chambers connected by a central tube (siphuncle). Even in Ordovician times there had already been a wide departure from the ideal simplicity of the *Orthoceras*. There were not only moderate curvatures, as exemplified by the *Cyrtoceras* (Fig. 160, *b*), but there were loosely coiled forms as the *Gyroceras* (Fig. 160, *f*) and close-coiled ones, as the *Tro-*

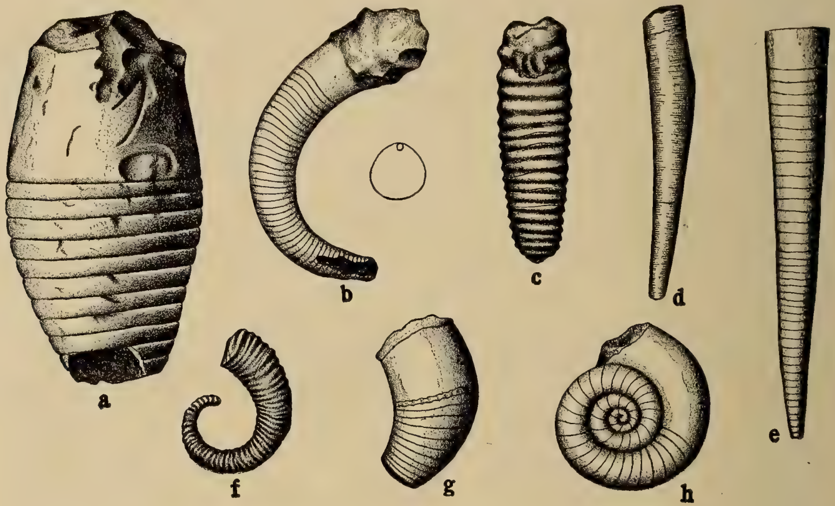

FIG. 160.—*Ordovician Cephalopods. a, Poterioceras apertum* Whiteaves; *b, Cyrtoceras neleus* Hall; *c, Orthoceras bilineatum* Hall; *d, Clinoceras mumiæforme* (Whitfield); *e, Orthoceras sociale* Hall; *f, Gyroceras duplicicostatum* Whitfield; *g, Oncoceras pandion* Hall; *h, Trocholites ammonius* Conrad. These figures illustrate different types of Ordovician cephalopods, varying from the straight orthoceratites (*e*) to the closely coiled nautiloid type (*h*). In all of them however, the sutures are straight or nearly so. (Weller.)

cholites (Fig. 160, *h*), which resembled the *Nautilus* of to-day. The straight forms preponderated, however, and the sutures scarcely departed from severe simplicity. We shall find that in later periods the septa and other features varied still more widely, and by so doing marked, in a very tangible way, the progress of the class.

Perhaps no other invertebrates so well show the progress of Paleozoic and Mesozoic times as the cephalopods, and this invites a special study of these early forms. The size attained in this early period was probably as great as ever reached by the chambered cephalopods, some of the shells being twelve or fifteen feet in length and a foot in greatest diameter. From this maximum they ranged down to forms smaller than a pipe-stem. Their habits are wholly matters of inference from their structure, and from the habits of their relatives in the present seas. Perhaps they floated, shell uppermost, or crawled upon the bottom, and preyed upon a variety of weaker forms of life.

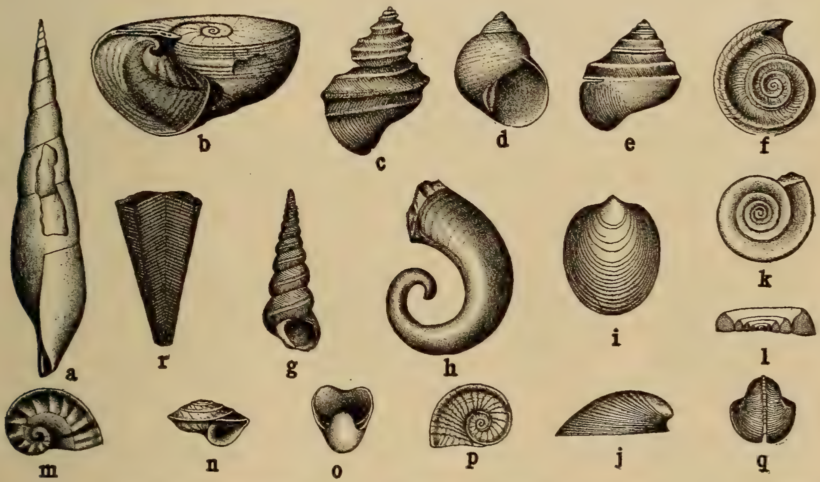

FIG. 161.—*Ordovician Gastropods.* *a*, *Subulites regularis* U. and S.; *b*, *Maclurea logani* Salter; *c*, *Lophospira helicteres* (Salter); *d*, *Cyclonema bilix* (Conrad); *e*, *Schizolopha textilis* Ulrich; *f*, *Helicotoma planulata* Salter; *g*, *Hormotoma gracilis* (Hall); *h*, *Eccyliomphalus triangulus* Whitfield; *ij*, *Archinacella cingulata* Ulrich; *k–l*, *Ophileta complanata* Vanuxem; *m*, *Cyrtolites ornatus* Conrad; *n*, *Raphistomina lapicida* (Salter); *o*, *Protowarthia cancellata* (Hall); *p*, *Conradella fimbriata* U. and S.; *q*, *Bellerophon clausus* Ulrich; *r*, *Conularia trentonensis* Hall. The exact zoological position of Conularia (*r*) is not certainly known, but it is usually regarded as a pteropod. The remaining figures illustrate in a measure the great variety of forms assumed by the Ordovician gastropods, a remarkable amount of differentiation when the slight representation of the group in Cambrian faunas is recalled.

The Ordovician gastropods.—The gastropods were very fairly represented in the early Ordovician fauna. There were present not only the simpler shell-forms, which consist merely of a low cone with a vertical or slightly curved axis, like the capulids (Fig. 161 *i*, *j*), but also the three leading types of the spiral shell, the depressed concave coil (Fig. 161, *k*, *l*), the low spire (Fig. 161, *n*) and the elevated spire (Fig. 161, *g* and *a*). The last made a relative gain as the period progressed. Perhaps no form of early Paleozoic life so closely and so obviously resembled the modern forms as the gastropods, which even the uninstructed recognize as "snails." The *Conularia* (Fig. 161, *r*) represents the suborder pteropods.

The Ordovician pelecypods.—The pelecypods (lamellibranchs), like their representatives (the clams) of to-day, seem to have been fond of muddy or sandy bottoms, for they are rather rare in the limestone beds of the earlier and middle Ordovician, but increase in abundance as the deposits grade into the shales of the later Ordovician. On the whole they were very subordinate to the gastropods and cephalopods in numbers and in range, except locally. This is perhaps the more

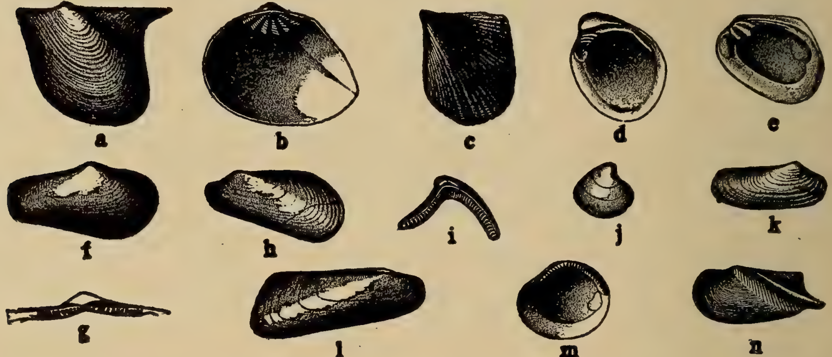

FIG. 162.—*Ordovician Pelecypods* (Lamellibranchs). *a*, *Pterinea demissa* (Conrad), exterior of left valve; *b*, *Lyrodesma cincinnatiensis* Hall, interior of right valve, showing a primitive type of hinge; *c*, *Byssonychia radiata* (Hall), exterior of left valve; *d*, *Vanuxemia dixonensis* M. and W., interior of right valve, showing the hinge and muscular impressions; *e*, *Ischyrodonta decipiens* Ulrich, interior of right valve, showing the hinge and muscular impressions; *f–g*, *Ctenodonta nasuta* (Hall), exterior of right valve and a view of the hinge; *h*, *Modiolopsis arguta* (Ulrich), exterior of the left valve, and a view of the hinge; *i–j* *Ctenodonta recurva* Ulrich, exterior of right valve and a view of the hinge; *k*, *Rhytimya radiata* Ulrich, exterior of the right valve, *l*, *Orthodesma rectum* H. and W., exterior of the right valve; *m*, *Ctenodonta pectunculoides* Hall, interior of the left valve, showing the hinge; *n*, *Technophorus divaricatus* Ulrich, exterior of the left valve. This is usually described as a pelecypod, but it is probably a peculiar bivalve crustacean.

notable, as the pelecypods are the lower and less differentiated type, though the hinged double valve is a device of higher order than the single valve. Representative forms are shown in Fig. 162.

The abundant development of the brachiopods.—Shells of brachiopods are the most common fossils of the Ordovician strata. This arose no doubt partly from their special suitability for preservation; but chiefly, we may safely assume, from their numerical superiority in the Ordovician fauna. The record, as it now stands, shows more individuals per species than in any other class except perhaps the bryozoans. This wide deployment is the more notable since the brachiopods were among the most conservative of all the classes found in the fossil state. The lower inarticulate forms of the order, which predominated in the Cambrian, continued through the Ordovician (as indeed they have done to the present time), but the higher articulate forms greatly outnumbered them. The large development of the articulate class was attended by a progressive evolution of the mode of articulation in which two lines were followed. In some the length of the hinge was increased, apparently affording a better means of resisting the attempts of their enemies to reach them by sliding or rotating the valves past one another (see Fig. 163, *a*, *b*, *e*, *f*, *g*, etc.). In others the front of the shell opposite the hinge was notched so that the valves were interlocked when closed, and thus more effectively resisted any sliding upon one another (Fig. 163, *d* and *u*). This device was usually best developed in the shells of narrow and weak hinge-line, where it was most needed (Fig. 163, *t–u*). Some shells combined both the long hinge-line and the interlocking front (Fig. 163, *c–d*). The hinges themselves were also improved by the use of different adaptations, not easily described briefly, but illustrated measurably in Fig. 163, *b*, *e*, *g*, and *q*. In addition to these devices for preventing the opening of the shell, there was generally a thickening of the shell walls, and in many cases a ribbing of the exterior which gave strength without needless weight, and at the same time facilitated the crenulation and interlocking of the front edge (Fig. 163, *d* and *u*). Correlated with these developments was also a deepening and strengthing of the muscular impressions, which implies a stronger and better muscular system (Fig. 163, *b*, *e*, *g*, and *i*). The introduction of the brachidium (Fig. 163, *z*), a calcareous support for the fleshy arms, is another notable advance.

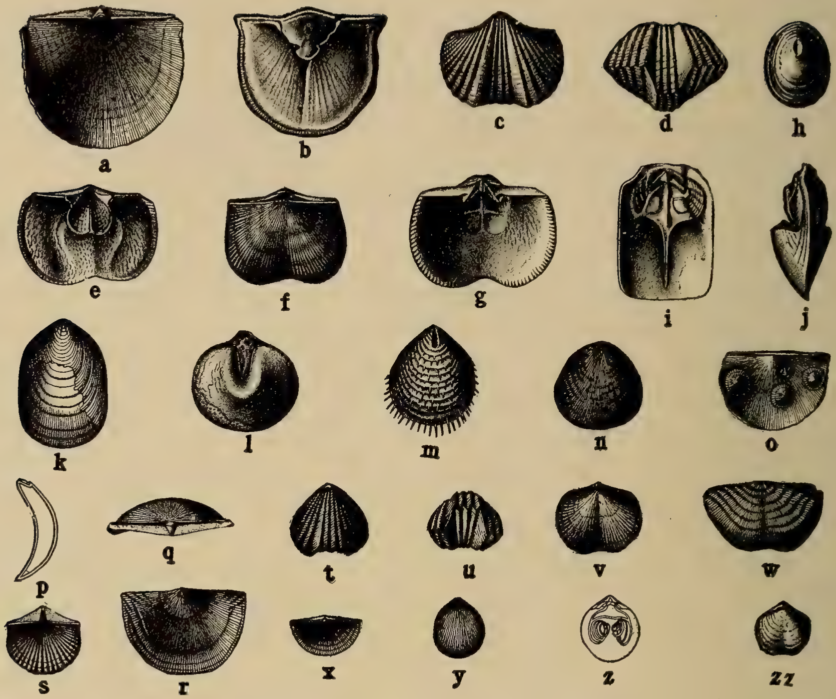

FIG. 163.—*Ordovician Brachiopods.* *a*, *Rafinesquina alternata* (Emmons), exterior of the concave brachial or dorsal valve, with the cardinal area and triangular deltidium of the pedicle valve; *b*, *Clitambonites anomala* (Schl.), interior of the pedicle valve, showing the spondylum; *c–d*, *Platystrophia lynx* (Eich.), exterior of the pedicle valve and anterior view of a complete shell, showing the fold and sinus; *e–g*, *Hebertella sinuata* (Hall), interior views of the two valves (*e*=pedicle, *g*=brachial), showing muscular impressions and hinge, and the exterior of a complete shell from the pedicle side; *h*, *Schizotreta ovalis* H. and C.; the pedicle valve; *i–j*, *Lingulasma schucherti* Ulrich, interior of the brachial valve, showing the elevated platform for muscular attachment, and the median septum; also a lateral view of an internal cast, showing the platforms in each valve; *k*, *Lingula rectilateralis* Emmons; *l*, *Trematis millepunctata* Hall, pedicle view of a complete shell, showing the unmodified notch-like pedicle opening; *m*, *Schizotreta fissus* Kutorga, a pedicle valve much enlarged; *n*, *Schizocrania filosa* (Hall), a brachial valve; *o*, *Crania lœlia* Hall, brachial views of four individuals attached to another shell; *p–r*, *Strophomena subtenta* Conrad, (*p*) profile view of the concavo-convex shell, (*q*) posterior view of a complete shell, showing the hinge-line, cardinal area, and deltidium, (*r*) exterior of the concave pedicle valve; *s*, *Orthis tricenaria* Conrad, exterior of the brachial valve and the cardinal area of the pedicle valve, showing the open delthyrium; *t–u*, *Rhynchotrema capax* Conrad, brachial and anterior views; *v*, *Dalmanella testudinaria* (Dal.), brachial view; *w*, *Leptœna rhomdoidalis* Wilck.; the pedicle valve; *x*, *Plectambonites sericeus* (Sow.), brachial view; *y*, *Catazyga headi* (Bill.), brachial view; *z*, *Zygospira recurvirostris* (Hall), interior of a brachial valve, showing the spiral brachidium in position; *zz*, *Zygospira exigua* (Hall), brachial view. Figures *h*, *i–j*, *k*, *l*, *m*, *n*, and *o* are inarticulate brachiopods belonging to the orders *Atremata* and *Neotremata*, and serve to illustrate in a measure the great variety of these brachiopods in the Ordovician fauna. The remaining figures are articulate brachiopods, *Protremata* and *Telotremata*. Figures *y*, *z*, and *zz* are spire-bearing *Telotremata*, which first appear in this period.

A comparison of the accompanying figures with those of the Cambrian brachiopods will illustrate, in some degree, these evolutions. All these devices seem to imply that the enemies of the brachiopods had increased in effectiveness also, perhaps in somewhat like proportions. That they did not gain undue mastery seems to be implied by the abundance of the brachiopods. A curious form was the concavo-convex type (Fig. 163, *p* and *q*), in which the living space between the valves was reduced almost to a minimum. Perhaps this also was an adroit protective device in that it gave so much shell for so little meat that it was scarce worth while for their enemies to crush them.

The abundance of the bryozoans.—The bryozoans were akin to the brachiopods, but their external forms, their habits of life, and their modes of depositing their hard parts were so different as to mask their kinship in the fossil form. The bryozoans lived in colonies, connected by a common mantle which secreted calcareous material to form the base or skeleton of the colony. These secretions so closely resemble those of the corals that they have often been classed as corals, and differences of opinion still exist relative to certain forms, the *Monticulipora* for example.[1] Certain bryozoan colonies formed hemispherical masses much like those of certain corals (Fig. 164, *b*). Others assumed branching forms, resembling the ramose corals (Fig. 164, *h* and *i*), while still others formed networks spread over other fossils (Fig. 164, *c*, *d*). The individual pit-like cavities, or cells (Fig. 164, *c*, *g*, *f*, and *j*) occupied by the individual bryozoans are usually much smaller than the cups of the corals, though the smallest cups of the corals are not larger than the largest cells of the bryozoans.

Judging by the fossils, the bryozoans were very rare in the Cambrian fauna, and were not very conspicuous in the early Ordovician, but they became abundant in the middle and later portions of the period, when they contributed an important element to the rock-material. The branched forms predominated, but the hemispherical and reticulated forms were not uncommon.

The deployment of the echinoderms.—While there is little more than a bare indication that the echinoderms were present in Cambrian time, before the close of the Ordovician period the cystoids had mounted to their climax, the crinoids had become prominent, and the asteroids, the ophiurians, and the echinoids had made their appearance, though scantily represented. This leaves unrepresented but one of the six classes susceptible of ready fossilization, the blastoids, and even these were foreshadowed by the blastoidean characters of some of the crinoids. Of all these, the cystoids were the most primitive in character and were doubtless most nearly like the parent stem from which all were derived, if indeed the cystoids were not the ancestral type. The irregular, unsymmetrical forms of the cystoids (Fig. 165, *a–f*) were gradually replaced by the more symmetrical and better

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[1] "The Problem of the Monticuliporoidea," F. W. Sardeson, Jour. Geol., Vol. IX, 1901 pp. 1–27.

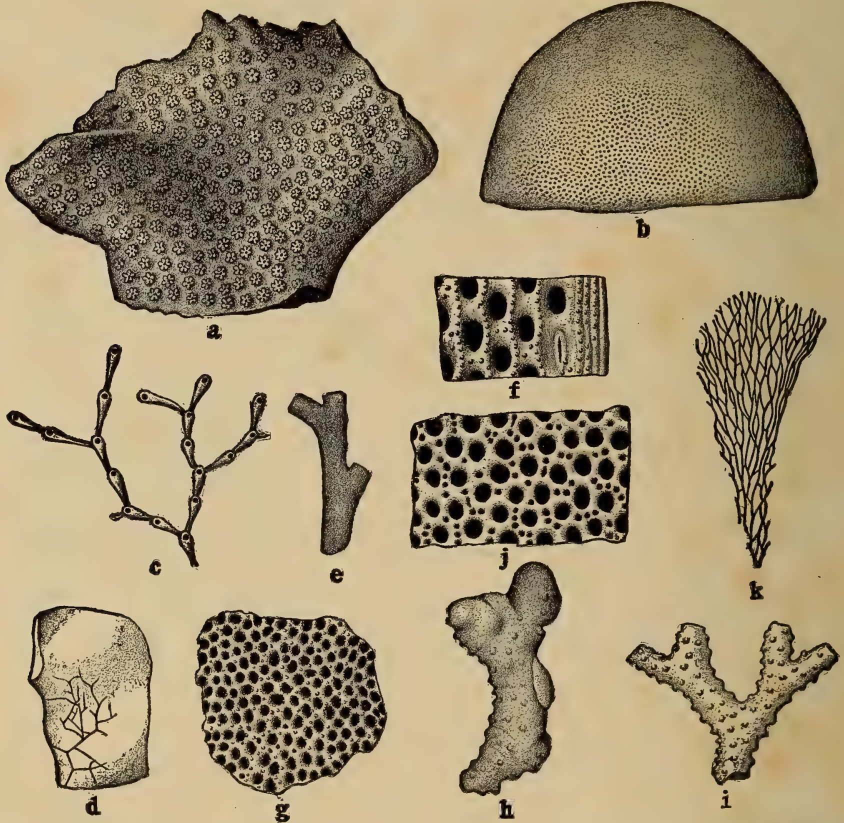

Fig. 164.—*Ordovician Bryozoans. a, Constellaria polystomella* Whitfield; *b, Crepipora hemispherica* Ulrich; *c–d, Stomatopora delicatula* (James); *e–f, Rhinidictya mutabilis* (Ulrich); *g–h, Monticulipora arborea* Ulrich; *i–j, Callopora pulchella* Ulrich; *k, Phylloporina granistriata* Ulrich. These figures represent a few of the almost innumerable forms of bryozoans present in the Ordovician faunas. At times they contributed a large portion of the calcareous matter of the limestones and calcareous shales.

organized crinoids (Fig. 165, *g–n*). Starfishes and serpent-stars (Fig. 165, *o* and *p*) are familiar modern forms. The crinoids may be likened to starfishes turned face uppermost and fixed to the sea-bottom by a stem attached to the center of the back. The body was gathered into a cup-like form composed of close-fitting plates arranged in pentamerous symmetry, and crowned by a fringe of arms variously and often elaborately branched (Fig. 165, *g–k*). The upper surface of the body cavity was in many cases closed over by a "vault" or arch formed of similar plates. The whole, aptly styled the calyx, more closely

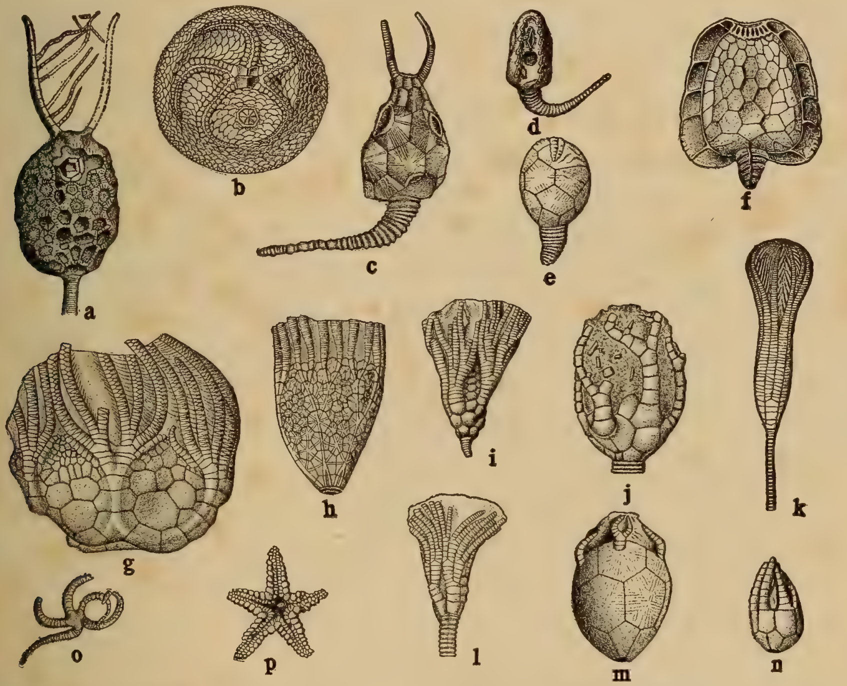

Fig. 165.—*Ordovician Echinoderms.* *a*, *Comarocystis punctatus* Billings; *b*, *Lepidodiscus cincinnatiensis* (Roemer); *c*, *Pleurocystis filitextus* Billings; *d*, *Glyptocystis multiporus* Billings; *e*, *Lepadocystis moorei* (Meek); *f*, *Mitrocystis mitra* Barrande; *g*, *Archæocrinus desideratus* Billings; *h*, *Glyptocrinus decadactylus* Hall; *i*, *Dendrocrinus polydactylus* (Shumard); *j*, *Anomalocrinus incurvus* M. and W.; *k*, *Ectenocrinus grandis* (Hall); *l*, *Iocrinus subcrassus* (M. and W.); *m*, *Carabocrinus vancortlandti* Billings; *n*, *Hybocrinus tumidus* Billings; *o*, *Tæniaster cylindricus* Billings; *p*, *Palæaster simplex* Miller. Figures *a*, *b*, *c*, *d*, *e*, *f* represent various types of cystoids from the Ordovician faunas. Figures *g*, *h*, *i*, *j*, *k*, *l*, *m*, and *n* are crinoids. These cystoids and crinoids constituted by far the greater element in the echinoderm fauna of the Ordovician. Figures *o* and *p* illustrate two types of the star-shaped echinoderms or *Asterozoa*, the serpent stars, or *Ophiuroidea*, *o*, and the true starfish, or *Asteroidea*, *p*. (Weller.)

resembled a flower in general aspect than an animal; and the familar name "sea-lily" is not inappropriate. Clad throughout in calcareous plates, the crinoids were excellent subjects of fossilization save that after the binding tissues decayed, the constituent plates easily fell apart and perfect specimens are rare. The stem, consisting of a series of disks ("little grindstones") perforated by a central canal, and rendered flexible by a minimum of integument, was disjointed with equal ease. Limestone is sometimes largely made up of crinoidal fragments.

The structure of the cystoids (Fig. 165, *a–f*) was very similar to that of the crinoids, but the body was unsymmetrical both in form and in the arrangement of the plates. The outline of the cystoid was sometimes spheroidal or ovate, sometimes sac-like or club-shaped, sometimes depressed and disk-shaped, with irregular departures from all these forms. A part or all of the plates were perforated by small pores connected with internal canals supposed to be concerned in respiration, this being perhaps the most vital ground of distinction from the crinoids, which do not usually show these. The arms were few and irregular, and sometimes wanting; the stem usually short and tapering, and often unattached.

Very little can be said regarding the evolution of the cystoids, for their forms are so heterogeneous and their functions so little known that it is not clear what constituted progress, and besides, they were so scantily represented in the preceding period, and so soon dropped away after the Ordovician, that an insufficient interval for comparison is afforded. The rise of the crinoids and the displacement of the cystoids by them is doubtless to be regarded as a phase of progress. The two classes lived in comparative abundance through the Ordovician period, and on into the Silurian, but by the close of the latter period the cystoids had greatly declined, while the crinoids were in the height of their abundance.

The asteroids and ophiurians (Fig. 165, *o* and *p*) were not abundant in the Ordovician, their chief development being reached much later than that of the two preceding classes. The same is even more true of the echinoids, which are barely represented in the strata of Europe.

The development of the cœlenterates.—Corals were sparingly present in the early part of the period, increased measurably in the middle portion, and somewhat more markedly toward the close, but they were not at any time a very prominent factor in the fauna. For the greater part they belonged to the simpler horn-shaped type (Fig. 166, *a*, *b*, and *c*). Compound corals, formed by colonies of polyps living together, were present (Fig. 166, *d* and *e*) and rarely formed reefs. The hydrozoan branch of the cœlenterates was represented by *Stromatopora,* which deposited thin films of calcium carbonate upon one another concentrically, giving rise to laminated masses somewhat resembling concretions and often distinguished from them with difficulty.

Much the most important development of the Cœlenterates was the rise of the graptolites, whose important function in correlation has already been discussed, and which will be further considered presently. Some of the typical forms are illustrated in Fig. 167.

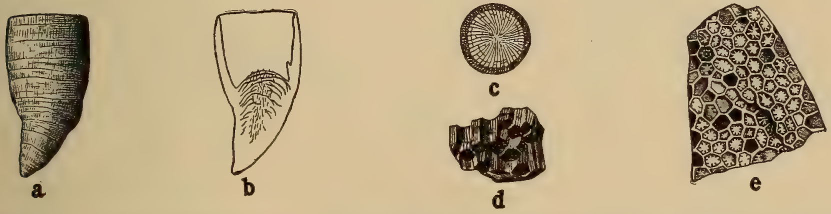

Fig. 166.—*Ordovician Corals.* *a–c*, *Streptelasma corniculum* Hall, exterior view with longitudinal and transverse sections, showing internal characters. *d*, *e*, *Columnaria alveolata* Goldf. While both simple and compound corals were present in the Ordovician faunas, they rarely formed great reef-like masses, as in later periods.

Other forms.—Sponges were present and sometimes attained notable sizes, but they played only a small part in the fauna (Fig. 168). Annelids were represented, but less abundantly than in the Cambrian, perhaps because the prevalently muddy and calcareous sea-bottom of the Ordovician was less congenial to them than the Cambrian sands. They are represented not only by burrows, but by teeth (Fig. 169). Protozoans were probably present, but their minute and fragile shells can be recognized only with some uncertainty.

Implied life.—If here, as in the discussion of the Cambrian life, we inquire what forms other than those fossilized are necessary to round out a rational assemblage of life, a briefer answer may be given, for the Ordovician fauna was a nearer approach to a theoretically complete assemblage. A vast supply of unrecorded vegetation must be postulated as a food-supply, as before, and to provide a complete chain of food-supplies for each one of the whole series of organisms that preyed upon one another in succession, from the plants up to the master forms of the predaceous animals, there must doubtless have been many intermediate species that are not now known. The defensive investitures of the lower forms, not fully accounted for by the known Cambrian species, are now much more nearly explained by the prevalence of the cephalopods and the presence of fishes; and the armorings of these dominant forms may have been defensive against their own kind. The fact that nearly all vegetal and animal tissue perished, and is not even represented by organic deposits save in exceptional cases, probably signifies that bacteria and allied forms that are concerned in the decomposition of tissue were present in abundance. What are interpreted as fossil bacteria are found a little later in some of the earliest vegetal tissues that are well preserved, and what seem to be the characteristic effects of bacteria on the tissues are also then recognized. This gives support to the view that the very general destruction of the tissues of the higher Ordovician animals and plants was the work of such destructive microorganisms. The paucity of the fossil record was therefore perhaps as

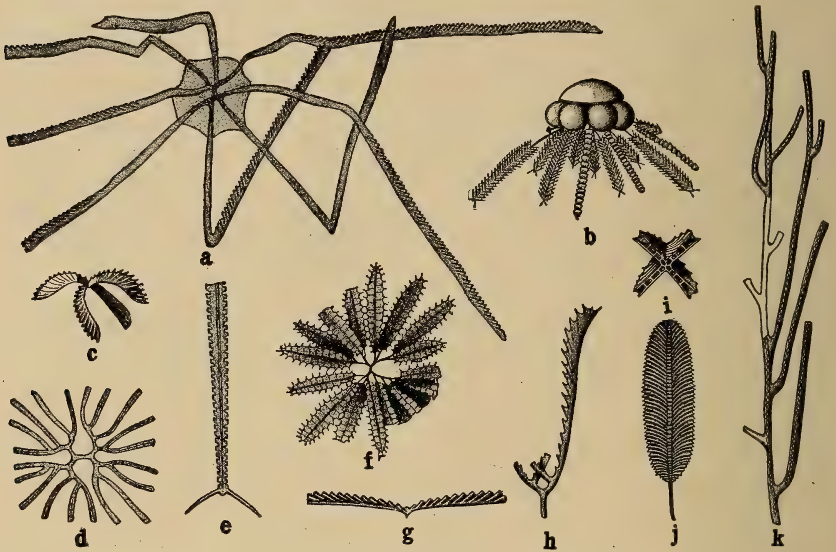

FIG. 167.—*Ordovician Graptolites.* *a*, *Dichograptus octobrachiatus* (Hall); *b*, *Diplograptus pristis* (Hall) (restored by Ruedemann); *c*, *Tetragraptus bigsbyi* (Hall); (*d*), *Dichograptus logani* (Hall); *e*, *Climacograptus bicornis* (Hall); *f*, *Reteograptus eucharis* Hall; *g*, *Didymograptus nitidus* (Hall); *h*, *Tetragraptus fruticosus* (Hall); *i*, *Phyllograptus ilicifolius* Hall; *j*, *Phyllograptus typus* Hall; *k*, *Holograptus richardsoni* (Hall).

much or more due to these as to unfavorable physical conditions. Rather paradoxically it may perhaps be said that the very scantiness of life relics is due to the abundance of certain forms of life.

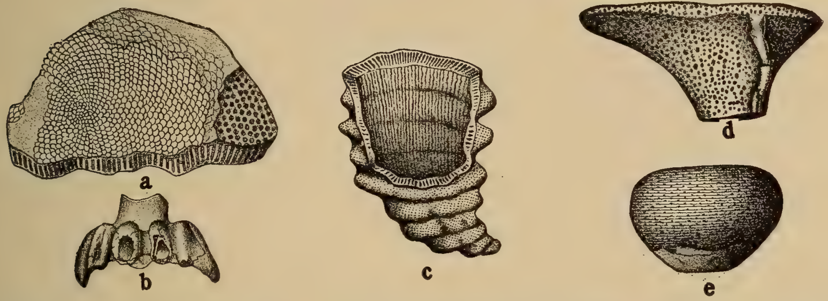

FIG. 168.—*Ordovician Sponges.* *a*, *Receptaculites occidentalis* Salter; *b*, *Brachiospongia digitata* Beecher; *c*, *Archæocyathus minganensis* Billings; *d*, *Strotspongia maculosa* U. and E.; *e*, *Ischadites*, species undetermined. The *Receptaculites* and *Ischadites* have sometimes been regarded as giant foraminifers.

Ecological, social, and mental development.—It is not necessary to more than briefly recur to the ecological, social, and psychological considerations to which attention was called in the discussion of the Cambrian life, for they remain essentially the same, save that the ampler development and better preservation of the Ordovician fauna give greater definiteness to the problems and supply more data for their elucidation. It seems clear that the adaptation of the various forms of life to one another and to their physical environment had reached a higher stage of adjustment, indeed a degree of adjustment not very greatly inferior to that which now prevails among the corresponding

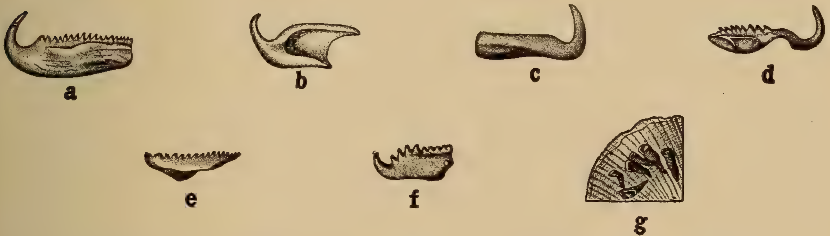

FIG. 169.—*Ordovician Annelids.* *a*, *Arabellites cornutus* Hinde; *b*, *Glycerites sulcatus* Hinde; *c*, *Eunicites gracilis* Hinde; *d*, *Arabellites ovalis* Hinde; *e*, *Eunicites varians* (Grinnell); *f*, *Oenonites rostratus* Hinde; *g*, *Ortonia minor* Nicholson. Figures *a*, *b*, *c*, *d*, *e*, and *f* are highly magnified illustrations of the jaws of annelids. Figure *g* is an example of the calcareous tubes secreted by some annelids attached to other shells.

orders; and it is not improbable that the mental development also approached somewhat nearly to that now possessed by correspondingly low types. Higher biological types within the same orders have certainly been developed since in many cases, and probably higher mental functions; but some of the Ordovician forms have since suffered biological degeneration, and probably also mental degeneration. The Ordovician ancestor of the barnacle, a free-moving active form, was doubtless superior to his sessile descendant of ill-repute. The sum total of ecological adaptation, and of social and mental development, however, seems to have advanced with each era, though perhaps not always with each of the briefer stages.

The Succession of Faunas.

1. **The Fauna of the Calciferous.**—The Calciferous in its typical development, in New York and the interior, is usually very poor in fossils, and these are poorly preserved. It is therefore difficult to find species that have a wide geographical range and yet are known to be so closely confined to this horizon as to be characteristic of it. Of the species so regarded the most widely available is the gastropod, *Ophileta complanata* (Fig. 161, *k* and *l*).

Certain genera are usually present, however, in most faunas of this age, among which may be mentioned *Tryblidium* and *Eccyliomphalus* among the gastropods, *Syntrophia* and *Camarella* among the brachiopods, *Orthoceras* and other genera among the cephalopods, and *Bathyurus* among the trilobites.

Doubtless many more or less imperfectly known species are really characteristic of the formation, but are not sufficiently prevalent and well preserved to give good evidence of it. Of connecting species, and hence not characteristic ones, there is a small list of which some range below and some above. For the greater part, the fossils are so sparse and so imperfect that their range and significance is not determinable. In the Champlain and the lower St. Lawrence Valleys where the formation is greatly thickened and appears to be less sharply distinguished from the formations below and above, a more ample fauna is found, and in it more species that range into the overlying and underlying formations. Thirty-five genera and one hundred species are announced from the vicinity of Lake Champlain, but the ranges of these have not yet been determined.[1]

In the shales of the Lévis formation in the lower St. Lawrence Valley many graptolites are found. These belong to the *Phyllograptus* zone, which embraces the subzones of *Tetragraptus* and of *Didymograptus bifidus*.[2] They represent a horizon corresponding to the Arenig of Great Britain. The *Tetragraptus* is regarded as marking the lowest horizon of the Ordovician. Of the graptolites illustrated in Fig. 157 those designated *a*, *c*, *d*, *g*, *i*, *j*, *k*, and *l* belong to the *Phyllograptus* zone, the most of them to the lower subzone. If this horizon could be traced to the interior, the lower limit of the Ordovician would there be fixed on excellent paleontological grounds and on an intercontinental basis. Unfortunately, the correlation of the graptolite-bearing Lévis beds of the St. Lawrence basin with beds in the interior is attended by grave difficulties on account of the contortion and faulting the Lévis has suffered, and the absence of graptolites from typical beds of the interior. The correlation has therefore been the subject of much difference of opinion. There appears to be a series of beds of great thickness below the Lévis that is referable to the Calciferous, which implies that the graptolite beds are not as old as the oldest Calciferous, but they have nevertheless usually been referred to the Calciferous, and the latter placed in the Ordovician. If, however, it shall ultimately prove that the *Phyllograptus* beds lie above the unconformity at the summit of the Calciferous in New York and its equivalent in the interior, or shall be found to represent that unconformity itself, the paleontological and the physical planes of division will be brought into harmony, and the original Calciferous will be referable to the Cambrian. There are graptolite beds in Arkansas and Nevada that belong to the same general horizon as those of the Lévis, though they present peculiarities, but they cannot be closely correlated stratigraphically with the original or typical Calciferous.

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[1] Brainard and Seeley, Bull. Geol. Soc. Am., Vol. I, 1890, pp. 501, 513; Vol. II, 1891, pp. 293, 300; Whitfield, ib., Vol. I, pp. 514, 515.

[2] Lapworth, Trans. Roy. Soc. Can., 1886; also Ann. Rep. Geol. Surv. Can., 1877–88, Part II, p. 45K; also Ann. Nat. Hist., 5th Series, Vol. VI, 1880, p. 197.

2. **The Chazy Fauna.**—The recorded fauna of the Chazy is much more ample than that of the Calciferous, and is closely related to the Mid-Ordovician fauna, of which it was an immediate forerunner in a closer and more obvious sense than was the Calciferous fauna a forerunner of the Chazy. *Maclurea magna* is regarded as the most characteristic fossil, and next to it perhaps is *Camarotœchia plena.* Other fossils regarded as essentially characteristic are the brachiopods, *Hebertella imperator*, *H. costatis*, *Dinorthis platys*, *Lingula lyelli*, *L. huronensis*, and *Rhynchonella orientalis;* the gastropods, *Pleurotomaria calyx*, *Metoptoma dubia;* the pelecypod, *Modiolopsis parviuscula;* the corals, *Columnaria incerta*, *C. parva*, *Streptelasma expansum;* the cystoids, *Malocystis murchisonia*, *Palæocystis tenuiradiatus;* the trilobites, *Bathyurus angelini*, *Amphion canadense*, *Amphyx halli*, *Harpes antiquatus*, *Illænus arcturus*, and the ostracode. *Leperditia canadensis.* Some species found in the Chazy range upwards into the Middle Ordovician and bind the Chazy fauna to it, and a few range down into the Calciferous. The Chazy fauna is fairly well characterized in the Champlain and St. Lawrence Valleys, but in the interior and west it is not distinctly differentiated, but appears to be lost in a larger assemblage of forms. It is hence inferred that it came in from the east and mingled with resident forms. Perhaps it developed in part in the St. Lawrence embayment before it was united with the interior sea after the stage of separation implied by the inconformity mentioned above. It is there that it has its closest relations to the Calciferous fauna, or at least to the eastern phase of that fauna.

3. **The Mid-Ordovician Fauna.**—While the special group of forms that con-

stituted the Chazy fauna probably came into the great interior sea of Mid-Ordovician times from the eastward, and thus contributed to its fauna by immigration, there is reason to think that other species had developed indigenously in the southern and western portions of that sea, and that still others came in from the other coast regions with which connections were had. In the Great Basin, Upper Cambrian species are found to mingle with Ordovician species through a notable vertical range. This implies that the transition was indigenous there, and that the sea was persistent. It seems also to imply either that the Cambrian fauna was prolonged there or that some species that are best known later in the Mississippi basin and the Atlantic province came in there relatively early; for example, *Orthis testudinaria,* which abounds in the Middle and Upper Ordovician of the Mississippi and Atlantic provinces and occurs in the Llandeilo (Mid-Ordovician of Great Britain), is found associated with *Dikellocephalus* and *Ptychoparia* (Cambrian genera) in Nevada.[1] In Tennessee and Kentucky there was a long period preceding the climax of the Mid-Ordovician fauna, during which there flourished an abundant fauna made up of species common in the interior and western regions, but only sparsely represented in the Chazy horizon of the Champlain-St. Lawrence embayment. These and similar facts warrant the view, which is to be held merely as tentative in the present state of investigation, that the Mid-Ordovician fauna of the interior is to be regarded, not as the simple successor of the Chazy fauna, or of any single earlier fauna, but as the common product of faunal elements derived from the coast regions on the various sides of the continent, commingled with resident forms that had evolved from the Cambrian fauna in the interior sea. This interior sea was much contracted on the north and east at the close of the Calciferous stage, but does not appear to have been wholly withdrawn. The contraction doubtless led to provincial evolution in the residual, more or less dissevered portions; but with the readvance of the sea that took place at the beginning of the Mid-Ordovician, the subfaunas so developed, commingled, and a common evolution took place. This Mid-Ordovician fauna is therefore only locally and partially to be regarded as the successor of the distinctive Chazy fauna or of any other invading fauna.

The Mid-Ordovician fauna was very prolific, and it is made to seem singularly so by contrast with the scantiness of the Calciferous fauna. It is not to be characterized by a few species, as in the preceding cases, but rather by the greatness, variety, and cosmopolitan character of its assemblage of thousands of species from various outside and inside sources of derivation. Its nature may be gathered by reviewing the forms illustrated in Figs. 157–169 inclusive, omitting the graptolites, a portion of the bryozoans, and a few other species specially mentioned under the other Ordovician faunas. The general aspect of these groups, when commingled, gives the general aspect of the Mid-Ordovician fauna. Locally there were modifications, such as gave rise to the Birdseye, Black River, Galena, and other special subfaunas of more or less local importance. There were also stages of progress common to wide areas that were marked by the incoming or outgoing of particular species or groups of species. These represent the evolution of the fauna in a broader sense. For the greater part these stages are yet to be worked out into precision and detail, though clearly recognizable in general terms.

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[1] Walcott, Pal. Eureka Dist. Mon., VIII, U. S. Geol. Surv., 1884, p. 1.

4. **The Upper Ordovician Fauna.**—The closing fauna of the Ordovician in North America retained most of the characteristics of the Middle fauna, from which it was directly descended without radical modification due to interruption of the controlling conditions. The chief change in the physical influences lay in an increased prevalence of silt sedimentation and in the shallowing and final withdrawal of the great epicontinental seas. With the development of the silt sedimentation there came a very notable increase, relatively at least, in the bryozoans (Fig. 161, *a* and *b*) and of the graptolites (Fig. 167, *b*, *e*, and *f*). The pelecypods were favored by the mud bottoms and became prolific. More than eighty species have been identified in a limited district in southern Ohio and Indiana.[1] There was a relative decline in the number of gastropods, cephalopods, and trilobites, and, in general, the fauna was perhaps less prolific; at least this appears to be so from the larger proportion of matter of inorganic derivation to that of organic derivation.

The closing phase of the Upper Ordovician was the withdrawal of the fauna of the interior as a necessary attendant of the withdrawal of the interior sea. The succeeding fauna contained an almost entirely new assemblage of species, though many of the genera remained the same. In the St. Lawrence embayment, the Ordovician fauna lingered longer and was gradually changed into or replaced by the Silurian fauna. Probably the same was true in other embayments on the border of the continent and along its coast generally.

The Ordovician Fauna of Other Continents.

Much the same general lines of progress were followed on other continents, and the general aspects of the successive subfaunas were much like those of the American continent. Usually the genera were the same, but the species as a rule were different, though they often bore a close resemblance to the American species. In northwestern Europe, with which the means of migratory communication seem to have been the freest, not a few common American species flourished, such as *Dalmanella testudinaria*, *Platystrophia biforata*, *Dinorthis porcata*, *Leptœna rhomboidalis*, *Plectambonites sericeus*, *Halycites catenulatus*, and *Trinucleus concentricus*. In Asia, so far as present limited information goes, the species were nearly all different, the wide-ranging graptolites excepted, though *Halycites catenulatus* and *Plectambonites sericeus* are found in China. The stages of progress in the shallow-water faunas of the Old and New World are to be regarded rather as parallel than as identical. The evolution in Europe, where alone details have been well worked out, was usually on less broad lines than that of the American interior, for the obvious reason that the epicontinental seas were more limited and more interrupted by barriers.

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[1] Ulrich, Geol. Surv. Ohio, Vol. VII, 1893, pp. 626–693.

CHAPTER VII.

THE SILURIAN (UPPER SILURIAN)[1] PERIOD.

FORMATIONS AND PHYSICAL HISTORY.

THE physical changes which brought the Ordovician period to a close marked also the inauguration of the Silurian. These changes, it will be recalled, involved (1) movements which affected small areas intensely (orogenic), and (2) movements which affected broad areas slightly (epeirogenic). From the standpoint of continental history, the gentler movements were the more significant, since they affected larger areas. It is not to be understood that these changes, whether orogenic or epeirogenic, were sudden or violent. Rather is it to be supposed that the formation of mountains and the emergence of large parts of the North American continent from the epicontinental sea which had covered it during the Ordovician period, occupied a considerable interval of time, including the later part of the Ordovician and the early part of the Silurian. After these changes had taken place, the area of land shown in Fig. 129 was greatly enlarged, was indeed more considerable than at any previous time since the early Cambrian (see Fig. 90, p. 220). With the increase in the area of land came lengthened streams, and presumably increased erosion, though the land areas were probably not of sufficient extent to give rise to streams equal in size to the largest of those of the present time.

Could the relations of land and water at the beginning of the Silurian be accurately defined, their statement would at the same time define in a general way the areas where the earliest sedimentation took place. Not only this, but it would also define in a general way the areas where sedimentation was rapid and where slow, for then, as always, such areas must have stood in more or less definite relation to the shores of the oceans. It is safe to assume that at the opening of the Silurian

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[1] When the name *Lower Silurian* is used instead of Ordovician, *Upper Silurian* is used in place of *Silurian*, as that term is here used.

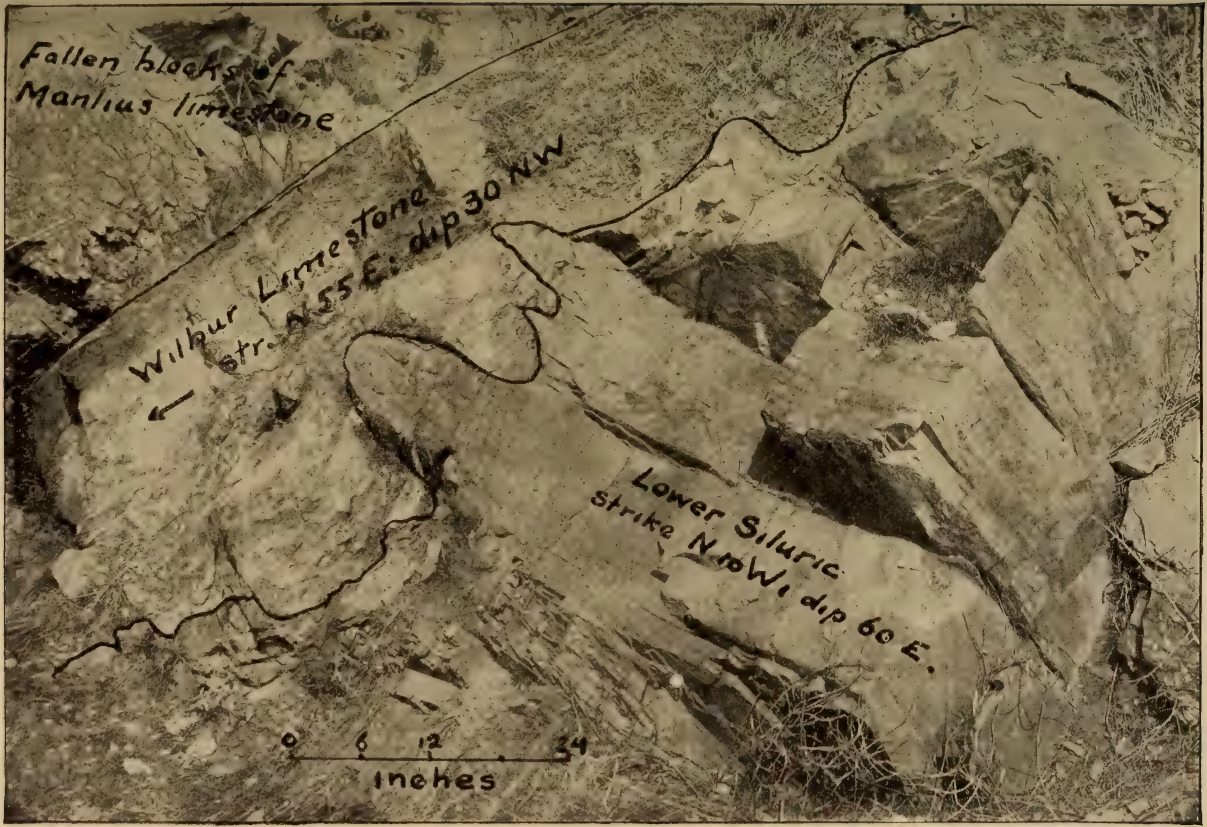

FIG. 170.—Unconformity between the Ordovician and Silurian. South end of Vlightburg, Rondout, N. Y. (Photo by Van Ingen, N. Y. State Geol. Surv.)

period beds of clastic sediments were accumulating about the immediate borders of the lands, and as far out as waves and currents were able to transport abundant detritus from the land, and that elsewhere sediments of organic origin were relatively more important. Though sedimentation was interrupted in the regions which emerged from the sea during the transition from the Ordovician period to the Silurian, it must be assumed that such interruption was not universal, and that where it did not take place, the Silurian strata are conformable on the Ordovician. It may be assumed further that at each stage of the Silurian period, the exposed portions of each older formation were contributing to the system then in process of formation. The areas of sedimentation at any particular stage of the Silurian cannot now be determined by the geography of that stage; rather is the geography of the successive stages of the period determinable in some measure by the successive areas of sedimentation.

SUBDIVISIONS OF THE SILURIAN SYSTEM.

The Silurian system of rocks is divided into a number of formations or series of formations. The principal subdivisions which have been commonly recognized in America are given below.

The Helderberg series, though sometimes classed as Silurian, is here classed with the next later (Devonian) system.

[(Lower) Helderberg?]
5. Salina
4. Niagara
3. Clinton
2. Medina
1. Oneida

In place of the above classification, the following has recently been proposed for New York:[1]

Ontaric [2] or Siluric	Cayugan Neontaric	Manlius limestone Rondout waterlime Cobleskill limestone Salina beds
	Niagaran (Mesontaric)	Guelph dolomite Lockport limestone Rochester shale Clinton beds
	Oswegan (Paleontaric)	Medina sandstone Oneida conglomerate Shawangunk grit

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[1] Clark and Schuchert, Science, Vol. X, 1898, p. 876, and Am. Geol., Vol. XXV, 1900. Slightly modified by Hartnagel, N. Y. State Mus. Bull. 69, 1903, p. 1160.

[2] The term Ontaric was first used in this sense by Emmons (Agr. of N. Y., Vol. I,

The principal subdivisions of this classification, modified as below, will be followed:

Silurian {
Cayugan
(Neo- or Upper Silurian)
Niagaran
(Meso- or Middle Silurian)
Oswegan
(Paleo- or Lower Silurian)

In this case there is some objection to the use of the terms Lower, Middle, and Upper Silurian, since Lower Silurian has been used as a synonym for Ordovician, and Upper Silurian for Silurian, as that term is here employed. The subdivisions in the third column of the above table (p. 370) are to be accepted for New York, but are not all applicable to other regions.

A brief sketch of the nature and distribution of these principal subdivisions of the system will throw much light on the history of the continent during the Silurian period.

THE OSWEGAN SERIES.

The Oneida formation.—The lowest and therefore the oldest formation of the Silurian system is the Oneida. It appears at the surface at various points in the Appalachian belt south of the Shawangunk (pronounced Shongum) mountains (N. Y.), though different names are applied to it in different regions, and it is not everywhere separated from the succeeding Medina. To the south, the formation seems to be restricted to the western part of the Appalachian system. Since the formation appears to rest conformably on the Ordovician, it is inferred that sedimentation was not interrupted, in the region where the formation occurs, during the transition from the Ordovician period to the Silurian.

The Oneida formation of the Appalachian belt is not known to extend west of the mountains, and it is now believed to have been accumulated in a narrow basin within the present Appalachian belt, completely shut off from the great interior (see Fig. 182, p. 390). It is not known whether the area where it occurs was submerged, or whether it was the site of subaërial deposition. The fact that the formation is without fossils lends color to the view that its sediments

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pp. 141–152), in 1846. It had been used earlier in a more restricted sense (Mather, Nat. Hist. of N. Y., Pt. IV, pp. 353–4.

were deposited on land, or in an enclosed body of water not freely connected with the sea. On the other hand, the materials of some parts of the formation are so perfectly assorted, and the pebbles so thoroughly rounded, as to suggest wave rather than stream work. If the formation is of marine origin, the coarseness of the sediments may help to explain the absence of fossils, for where coarse sediments are gathering, shells are more likely to be destroyed, and so far as they are buried, they are likely to be dissolved at a later time because of the free circulation of water through the porous beds.

South of Lake Ontario there are beds which have been classed as Oneida. They are fossiliferous and clearly associated with the Medina formation of the region. They are believed to have been deposited in waters which were separated from the Appalachian basin already referred to. The term Shawangunk, applied to the eastern beds, is not applied to the more westerly ones.

The Shawangunk (or eastern Oneida) formation is about 500 feet (maximum) thick in New York, and 800 feet in Pennsylvania. Both in its constitution and structure it bears the marks of shallow water (or subaërial) deposit, being chiefly of sandstone and conglomerate, often cross-bedded and ripple-marked. The materials of the formation seem to have been derived from older lands to the east. They are essentially quartzose, and represent the products of rock decay rather than of rock breaking. The abundance of quartz pebbles suggests that the metamorphic rocks of Appalachia had long been undergoing decay before the advent of the Oneida epoch, but that the land surface had stood so low as not to allow of the removal of the coarser products of decomposition. If, following such a period, the land were elevated, rejuvenating the streams, such material as that of which the Oneida formation is composed would have been washed down to the sea or to low-lying lands. The character of the Ordovician beds (limestone and fine sediments) in the region of the Oneida formation is consistent with the sequence of events here suggested.

The Oneida formation, composed at the outset of durable materials, has been so thoroughly indurated by compression and cementation as to become exceedingly obdurate. The outcropping edges of its tilted beds (Fig. 171) constitute the crest of the Kittatinny range in New York, New Jersey, and Pennsylvania (Fig. 172). Not only does the Oneida conglomerate constitute the crest of this range, but the range owes its existence to the obduracy of this rock, which successfully withstood erosion while the less resistant formations to the east and west were carried away. The same formation (the Green Pond Mountain conglomerate) appears also in the Green Pond mountain of New Jersey, and in its northward continuation in New York. The outcrop of the Oneida is also conspicuous farther south, and for the same reason.

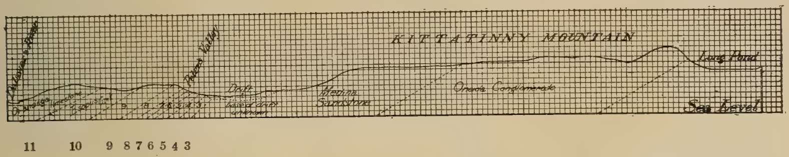

FIG. 171.—A section across the Kittatinny Mountain in northwestern New Jersey. Length of the section, about five miles; vertical scale, nearly twice the horizontal; angle of dip, approximately doubled. 3=Poxino Island shale; 4=Bossardville limestone; 5=Decker Ferry beds; 6=Manlius limestone and Rondout limestone; 7=Coeyman limestone; 8=Becraft limestone, New Scotland beds, and Stormville sandstone.

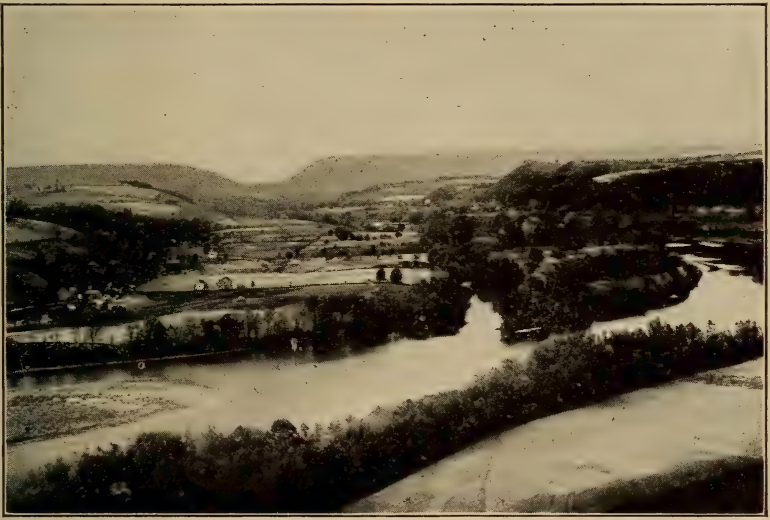

FIG. 172.—The Delaware Water Gap. The crest of the mountain range seen in the background is the crest of the Kittatinny range made by the resistant Oneida conglomerate.

The Medina formation.—The Medina formation, consisting of sandstone and shale (including the Longwood shale of the Green Pond Mountain region), overlies the Oneida. Its materials, like those of the Oneida, appear to have been accumulated in shallow water, or possibly on land. This is shown by the cross-bedding, the ripple-marks, etc., which affect the surfaces of its layers. In view of these facts, and in view of the physical similarity of the two formations and of the conformity of the younger on the older, it is inferred that the deposits of the Medina stage followed those of the Oneida without interruption where both formations are present. Like the eastern Oneida, the eastern (Appalachian) Medina seems to have been deposited in a basin which had no connection with the interior. Beds classed as Medina are also found south of Lake Ontario, where they overlie the Oneida of the same region. They appear at the surface as far west as eastern Ohio and Ontario, where they thin out and disappear. West of this longitude, the formation has not been identified.

The Oneida and Medina formations south of Lake Ontario contain marine fossils, showing that an interior sea existed in this region in early Silurian time. The distribution of the two formations indicates a more extended sea in the later than in the earlier epoch, and points to a subsidence of the eastern interior during the early part of the Silurian period. By the close of the Medina epoch, as the distribution of the Medina formation shows, the area of deposition had been extended at least as far west as Ohio (the Cincinnati arch).

The Medina formation, which has but a narrow outcrop in northern New York, is probably continuous beneath younger strata over most of the state south of Lake Ontario and the Mohawk valley, and west of the Appalachian basin, and farther south over considerable areas west of the Appalachians. Nothing is known of the sediments which must have been accumulating along the eastern border of Appalachia, nor of those about the other land areas of the time. Though the Oneida and Medina formations are unknown both in the interior west of Ohio and in the western part of the continent, it is possible that strata which are their time-equivalents exist in some parts of this vast territory. If they anywhere appear at the surface, they have not been identified.

In Pennsylvania, the eastern (Appalachian) Medina formation has a maximum thickness of something like 1800 feet. This, it is to be remembered, was near a great land-area to the east whence the sediments were doubtless derived. West of the Appalachian belt the formation is much thinner, having in Ontario a thickness of 300 to 400 feet. The material for that part of the formation which lies in northern New York and Ontario probably came from the north. The lesser thickness of the formation in this region, as compared with that of Pennsylvania, suggests either that the rate of accumulation was slower, or that the formation in Ontario does not represent the full series of beds belonging to the epoch.

The Niagaran Series.

The Clinton formation.—The formation next younger than the Medina is known as the Clinton formation. Where the younger formation overlies the older they are generally conformable, but the distribution of the two is so different as to indicate that geographic changes of importance were in progress as the Silurian period advanced. The Clinton formation extends farther east and farther west than the Medina, indicating an expansion of the eastern interior sea in both directions. To the westward the Clinton extends to Lake Huron and Indiana, and perhaps to northern Illinois and eastern Wisconsin, and even to northeastern Missouri. If it extends so far west, it is made up of beds which have usually been classed as Niagara. It is not known whether the Cincinnati arch was submerged at this time, or whether it was an island in the Clinton sea. Southern Indiana and southern Illinois seem not to have been submerged. The Clinton formation also occurs in the Appalachian mountains as far south as Alabama and Georgia. It seems probable from the evidence now in hand that the elongate basin in which the sediments of the Clinton formation of this mountain belt accumulated was separated from the interior sea, or at least not freely connected with it. This inference is based chiefly on the dissimilarity of the faunas of the beds classed as Clinton in the Appalachian belt and in the interior.

Sedimentary beds which are believed to belong to the Clinton epoch have been recognized in Nova Scotia (a part of the Anticosti series) and at a few other places northeast of the United States. In this region marine sedimentation was probably continuous through the Ordovician and Silurian periods, and the correlation of the strata with those of the interior is attended with difficulty and uncertainty. The materials for these beds, so far as clastic, were probably derived from land to the west.

The variations in the character of the Clinton beds in different localities are not without significance. In the Appalachian mountains, the Clinton sediments were largely sand and mud, now in the condition of sandstone and shale. In western New York and beyond, much of the formation is limestone, showing that the seas of that region were relatively clear, and that organic sediments predominated over clastic. Bryozoan reefs, resembling coral reefs, occur in this formation in western New York.[1] The limestone does not mean that the water was necessarily deep, but rather that the water in which it was deposited was so nearly free from clastic sediments that the shells, etc., constituted the principal part of the deposit made. Shell-bearing life may be just as abundant where sand and mud are accumulating as elsewhere, but in this case the product is not limestone, but sandstone, shale, etc., containing shells.

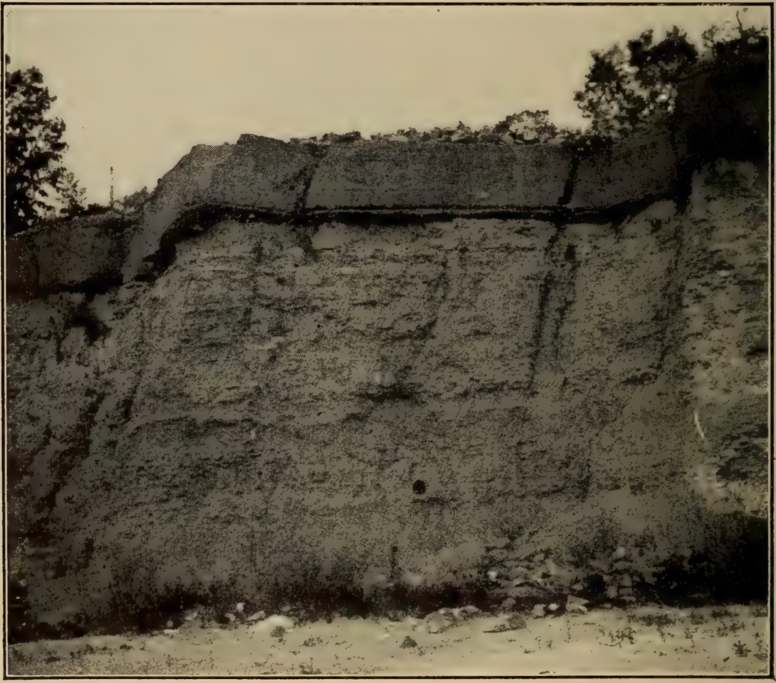

Fig. 173.—The Clinton formation with Niagara overlying. Howe's Cave, N. Y. (Darton, U. S. Geol. Surv.)

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[1] Sarle, Am. Geol., Vol. 28, p. 282.

One of the notable features of the Clinton formation is the presence in it at many points of iron ore. Chemically, the ore is generally in the form of hematite. Physically, it is often made up of small concretions which so resemble flaxseed in size and shape as to have suggested the name "flaxseed" ore. Locally it is known also as "fossil" ore from the abundance of fossils which it contains. The ore is known at many points between New York and Alabama,[1] as far west as Wisconsin [2] (where it is the only representative of the formation which has been commonly recognized), and as far northeast as Nova Scotia. The ore beds are interstratified with other beds of the formation, and are usually believed to have been accumulated by chemical precipitation in marshy flats. Since the iron compounds in solution in the water were derived from rock formations in process of decay, the extraction of these compounds being itself one of the elements of decay, the iron ore, as well as the other beds of sedimentary rock, had its origin in the decay of the older formations. The iron was probably deposited in the form of limonite ($2Fe_2O_3$, $3H_2O$) or of iron carbonate ($FeCO_3$), and subsequently changed into its present form (Fe_2O_3). This is the fourth series in America which contains a large amount of iron ore, the first, second, and third being in the Archeozoic, the Huronian, and Animikean respectively. Like the Clinton iron ore of Wisconsin, the manganese ore deposits [3] of Arkansas lie at the base of the Silurian system in that region, and the two classes of ore may have had a somewhat similar origin.

The Clinton formation has a thickness of 900 or 1000 feet in Pennsylvania, of 800 in Virginia, and of 200 or 300 feet in eastern Tennessee and Kentucky. In the eastern interior, the formation is much thinner.

Like the Oneida and Medina formations which preceded, the Clinton beds have not been identified in the western half of the continent.

The Niagara formation.—The Clinton formation of the interior was succeeded by the Niagara (Rochester shale, Lockport limestone, and Guelph dolomite of New York; see p. 370), which extends somewhat farther west than any of the preceding Silurian formations, showing that the submergence of the earlier epochs still continued in the Upper Mississippi basin. The Niagara formation covers not only much of New York, Ontario, and Ohio, but also all or nearly all the southern peninsula of Michigan, much of Indiana and Illinois, and parts of Wisconsin and Iowa. North of Missouri, it is not known to occur far west of the Mississippi. It was formerly supposed to be present in the Black Hills of South Dakota, but this correlation seems to be doubtful.[1] It may yet be found where it has not been recognized, or where its identification has not been placed beyond question. The formation probably never extended east over the Cincinnati arch or the similar Nashville dome to the south, though it extended east between them. To the westward it extended beyond the Mississippi into eastern Missouri, Arkansas, and perhaps even to the Arbuckle mountains in Indian Territory. It was in this epoch, as the relations of the next succeeding formation show, that the submergence which had been in progress since the beginning of the Silurian period, reached its maximum in the upper Mississippi basin. In the southeastern part of the same basin, the sea of the Niagara epoch was probably more restricted than that of an earlier time.

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[1] See geological reports of the several States; also Jour. Geol., Vol. IX, p. 412.

[2] Geol. of Wisconsin, Vol. I, 1881.

[3] Penrose, Geol. Surv. of Arkansas, Vol. I of the Ann. Rept. for 1890.

The southern border of the interior sea is not known, but it appears not to have been connected with the ocean in this direction. The land barrier which limited it on the south appears to have been in the position of the Gulf States. These general facts are expressed on the map, Fig. 174.

Beds of sedimentary rock contemporaneous with the Niagara of the interior may exist in the northern part of the Appalachian belt, but their faunas are so unlike those of the Niagara of the Mississippi basin as to indicate the continued separation of the Appalachian basin from the interior. Because of these conditions, exact correlations between the second group of the Middle Silurian series (p. 371) of the interior, and the corresponding beds of the Appalachian trough, have not been made.[2] The upper part of the Niagaran series (above the Clinton) is believed to be absent from the southern Appalachians, the region where most of the preceding formations of this period and of the Ordovician are well represented. Their absence from this region appears to mean that the shore of the interior sea was temporarily shifted to the west, either because of crustal movements which caused

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[1] Beecher, Am. Geol., Vol. XVIII, p. 31.

[2] Weller, Rept. on the Paleozoic Paleontology of New Jersey, Geol. Surv of N. J. 1903.

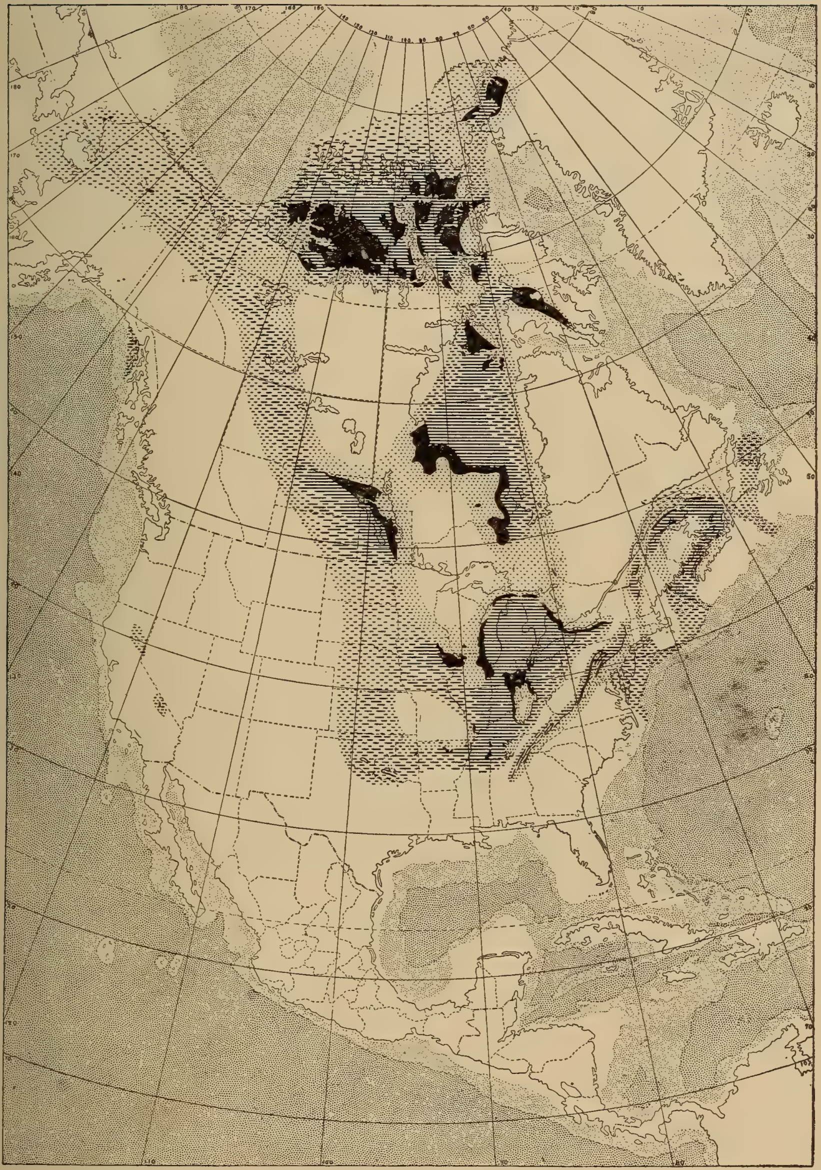


FIG. 174.—Map showing the outcrops of the Niagara formation, and at the same time the general relations of land and water during the Niagara epoch. The various sorts of shading on the map correspond with those on earlier maps (see p. 220).

the land to emerge, or because the sea-bottom had been converted into land by aggradation.

A significant feature of the distribution of the Niagara formation to be associated with its distribution in the interior of the continent is its great development in high latitudes. It occurs in Manitoba, and from here probably extends down into Minnesota. While this area of Niagara is not known to be connected with that of Iowa and Illinois, such connection is probable, being now obscured by the heavy body of drift which covers most of Minnesota. The Niagara formation is also present west of Hudson Bay, and over numerous large and small areas on the continent and on islands between the parallels of 60° and 76°. It is also present in Grinnell Land and Greenland in latitude 80°.

The isolated areas of the Niagara formation in these northern regions appear to be remnants of a once continuous body. This inference is rendered probable by the similarity of the fossils throughout the northern area. From the same line of evidence, it is inferred that there was shallow water connection between the Mississippi basin and northern Europe by way of the arctic islands, a connection which permitted the intermigration of the shallow-water animals of the two regions.

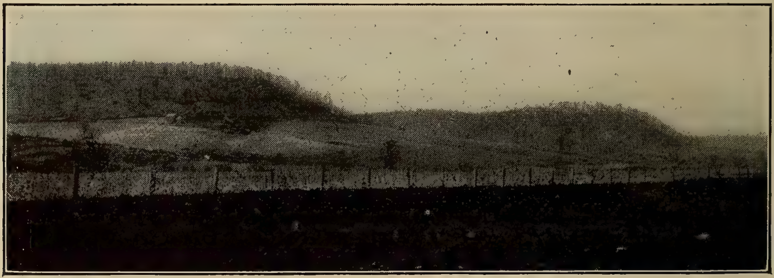


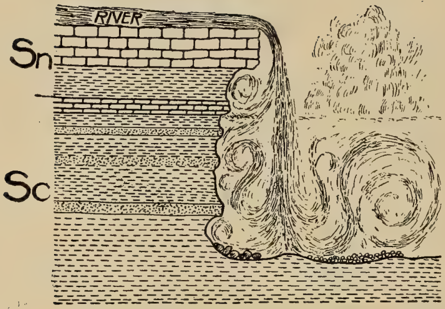
Fig. 175.—Contact of the Niagara limestone and the Maquoketa (Hudson River shale) in northeastern Iowa. The view illustrates the effect of inequalities of hardness on topography. The cultivated surface with the gentle slope is underlain by Hudson River shale; the wooded slopes above are the escarpment of Niagara limestone. (Calvin, Iowa Geol. Surv.)

Between the northern areas of exposed Niagaran, older formations from which the Niagara has been removed are exposed. In the United States, on the other hand, the more or less widely separated areas of exposed Niagara are separated because the formation is concealed at intervening points by younger beds.

The distribution of the Niagara formation in the interior, taken with the distribution of the earlier Silurian formations, would lead to the conclusion that the Niagara should rest on the Hudson River shales unconformably over a large area in the Mississippi basin. Such is doubtless the fact, yet the degree of unconformity is so slight as not to be readily detected. This might mean either (1) that the older formation was elevated so little at the close of the Ordovician, and stood so low during the Oneida, Medina, and Clinton epochs, as to have suffered little erosion, or (2) that it was almost perfectly base-leveled before the Niagara epoch. In both cases it would be necessary to suppose that the strata were little deformed, since the bedding of the two formations is essentially harmonious. Between these two alternatives, the former is perhaps the more probable.

In New York the beds which were formerly grouped under the name Niagara, and now under the series name, Niagaran, consist of shale (Rochester, p. 370) below, and limestone (Lockport and Guelph) above. It is the more resistant beds of the latter overlying the more yielding layers of the former (Fig. 176) which have given rise to the Falls of the Niagara, the locality whence the formation takes its name, and determined the position of the escarpment between Lake Ontario and Lake Erie (Fig. 177) from which the Falls (at *F*) has retreated. The same limestone has determined other falls, such as the uppermost falls of the Genesee river, shown in Fig. 178. West of New York the formation is mainly limestone. Except the Trenton, it is more wide-spread than any preceding formation of limestone, and tells of an expanse of clear water covering much of the great Mississippi basin.

The Niagara formation is the oldest in which well-developed coral reefs have been identified. While coral-secreting polyps had lived before, as shown by their abundant fossils in older formations, and while their secretions had helped to make the Trenton and other limestones, the reef-building species seem to have first become abundant in mid-Silurian time. The reefs are known in eastern Wisconsin and at other points farther south and east. Coral reefs and the adjacent deposits illustrate as clearly as anything else among the ancient formations the methods by which limestone deposits were formed. The reefs themselves are composed of the commingled relics of the life that grew upon them. Great masses of coral may sometimes be seen standing erect in the rock precisely as they grew, having entirely escaped



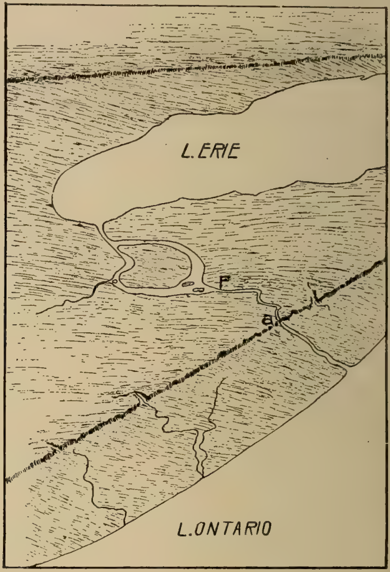


FIG. 176. FIG. 177.

FIG. 176.—Diagrammatic section showing the relations of rock formations at Niagara Falls. (Gilbert.)
FIG. 177.—The Niagara escarpment. (Gilbert.)

destruction during their burial in the growing reef. In other instances the coral masses represent remnants only, the greater portions having been broken down and worn away by the waves, or dissolved by the ocean waters, soon after their formation. At various points there are

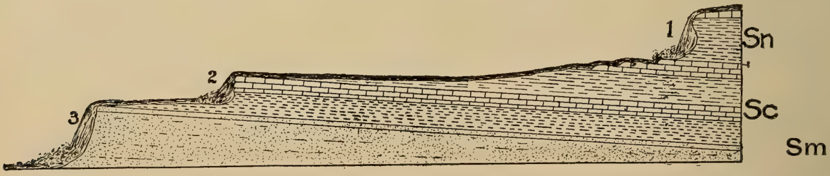


FIG. 178.—Diagrammatic section showing the relations of various sorts of rock at Genesee Falls. (Hall.)

detached fragments showing various degrees of wear, together with coarse and fine detritus, the product of coral comminution. These combine to make up the mass of the reef-rock. Locally there is evidence that some of the limestone after having once been solidified was broken up by the waves and re-deposited, forming a coarse, brecciated mass. In such cases the spaces between the fragments are often filled with fine detritus in which fossil shells sometimes occur, as though the shell-bearing animals had sought the protection of these sheltered nooks, or as if their shells had been driven thither by the waves. Evidences of wave-worn hollows and recesses in the reefs may also be found, showing that waves were then wearing, as now, the summits of rock-masses which were so slightly submerged as to come within the limits of their action.

The deposits between and about the ancient Wisconsin reefs are similarly instructive. On the sides and at the bases there accumulated a mixture of shell and coral fragments and calcareous sands growing finer and finer as the distance from the parent reef increased, and the slope of the bottom became more gentle, until at a distance, having passed through the several granular stages, there was a gradation into white calcareous mud, which spread itself widely over the sea-bottom around the reefs and between them and the adjacent land. This fine calcareous sediment ultimately gave rise to the compact white limestone of the region.

On the submarine plains immediately bordering the reefs flourished many forms of life which secrete lime carbonate. Mollusks and crinoids seem to have been more abundant here than upon the reefs themselves. Over the white mud-flats beyond there seems to have been a relative paucity of life, the reef-frequenting forms being especially rare.

In the ancient Niagara seas, therefore, at least four phases of limestone were in process of accumulation simultaneously, viz.: (1) that composed of coral which still remains unbroken; (2) that composed of masses of coral partly disrupted; (3) that made up of the granular products of shell and coral grinding; and (4) that made up of the still finer products of comminution, all derived from essentially the same source, the secretions of the reef life. To this category should perhaps be added (5) the brecciated limestone, made up of the broken and recemented fragments of beds which had been disrupted, and (6) the oölitic limestone which occurs at some points in this and many other limestone formations. The especial feature of this variety of limestone (Fig. 179) is that it is made of tiny concretions of lime carbonate precipitated from solution about nuclei of any sort. Recent observations have shown that the conspicuous beds of chert nodules in the dolomitic Niagara limestone of the Chicago area are in reality great sponge beds. The minute spicular structure of these organisms may be frequently detected under the microscope in thin sections of these nodules (Fig. 179*a*), although in most of them these structures have been nearly or wholly obliterated.[1]

East of the Appalachians and west of the Mississippi the distribution of strata of Niagara age is not generally known in detail. Limestones which are perhaps referable to the Niagara occur in New Hampshire and Maine,[2] and in the Provinces between these States and the St. Lawrence. In Nova Scotia the formations of the Niagara epoch are represented by 1300 feet of shales, affording another illustration of the fact that very different sorts of rock may be accumulating in different regions at the same time.

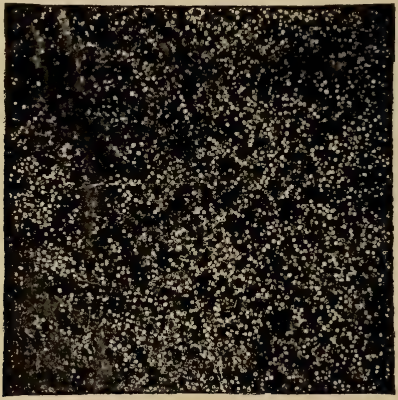


Fig. 179.—Oölitic limestone.

Like the older formations of the Silurian, the Niagara has not been identified with certainty in the western part of the continent.

Unlike the preceding formations of the Silurian, the Niagara is not thicker in the east than elsewhere. In the east, indeed, where the formation is exposed it has a thickness of but 100 to 300 feet, while in Wisconsin[3] it attains a maximum of 800 feet (probably including some Clinton), all of which is limestone. It would appear that the land along the eastern border of the continent was not yielding abundant sediments to the sea lying west of it. This was probably because the land was low, and it may have been low either because it had sunk or because it had been nearly base-leveled in the preceding epochs. The slight thickness of limestone in the east (New York) as compared with the west (Wisconsin) remains to be accounted for. If the Niagara of the west, as commonly classified, includes beds which are the time-equivalents of the Clinton of the east, this would help to account for the greater thickness of the Niagara of the west. Again, it may be that the sorts of life which produce limestone were more abundant in the west, a suggestion which the coral reefs, as well as other fossils of that region, strengthen.

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[1] G. F. Harris, personal communication.

[2] Williams, Bull. 165, U. S. Geol. Surv.

[3] Geol. of Wis., Vols. I and II.

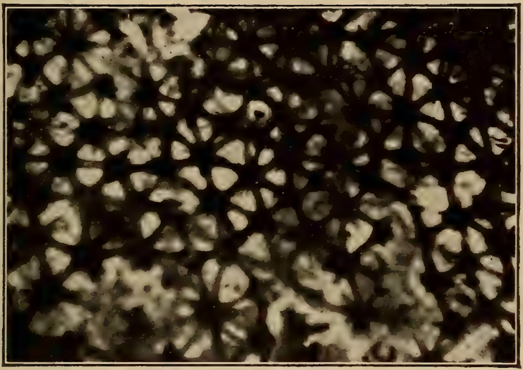

Fig. 179*a*.—Photograph of a section of a chert nodule from the Niagara limestone near Chicago, showing sponge structure. (From G. F Harris.)

The Guelph dolomite (Fig. 180) is distinguished from the Lockport dolomite in western New York by the presence of a different fauna. This fauna is, however, not restricted to beds overlying the Lockport dolomite, but occurs as represented in Fig. 180. This section appears to mean that the locality where it occurs was near the border of two regions inhabited by different but contemporaneous faunas, and that these faunas alternately had the advantage in the struggle for dominance.[1] If this interpretation be correct, the Guelph and Lockport dolomites are, in part at least, contemporaneous.

While the Niagaran beds of the interior are in general nearly horizontal, they are frequently domed so as to give the beds a high angle of dip. This is true at some points in eastern Wisconsin, about Chicago, and at points in Indiana. (Fig. 181.)

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[1] New York State Museum, Memoir 5, 1903, pp. 4–22.

The Salina (Cayugan) Series.

The Salina series.—The formation or group of formations next succeeding the wide-spread Niagara limestone differs from it so widely both in distribution and character as to indicate that considerable geographic changes had intervened. It extends somewhat farther

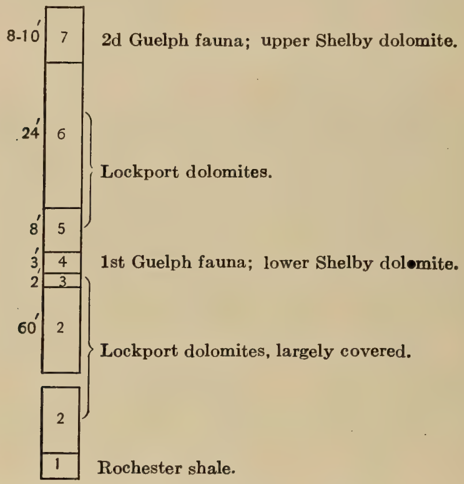
8-10'
7
2d Guelph fauna; upper Shelby dolomite.
24'
6
Lockport dolomites.
8'
5
3'
4
1st Guelph fauna; lower Shelby dolomite.
2'
3
60'
2
Lockport dolomites, largely covered.
2
1
Rochester shale.

Fig. 180.—Figure showing the relations of the Guelph to the other members of the Niagaran series. (New York Geol. Surv.)

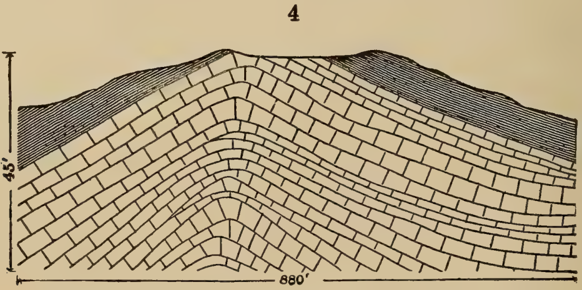

Fig. 181.—The Wabash dome in the Niagara limestone. (Kindle.)

east than the Niagara, and occurs in the Appalachians of Pennsylvania and farther south, where the Niagara is not known to be present. To the west, on the other hand, the Salina formation is restricted to much narrower limits than the Niagara. Like the latter, it underlies much of southern and southwestern New York, and probably western Pennsylvania as well, and extends west into Ohio. It is also present in Ontario, and extends thence to the northern extremity of the southern peninsula of Michigan, and to the eastern border of Wisconsin, but it is not known in Illinois, or at any point farther west in the basin of the Mississippi. If it now exists in these States, it has not been identified.

The absence of the Salina formation from so great an area where the Niagara is present, points to the emergence of a considerable area in the Mississippi basin at the close of the Niagara epoch, and the nature of the Salina series, where present, shows that geographic relations were greatly altered. A map showing the relations of land and water during the Salina epoch would show a great increase in land over that shown in Fig. 174.

In the east, the Salina group embraces three principal varieties of rock—limestone, shale, and rock salt. With these formations, some gypsum, the usual concomitant of salt beds, is associated. Shales constitute the larger part of the group, and seem to have originated after the fashion of shales in general, but their meager content of fossils seems to point to their deposition under conditions unfavorable for life.

The salt is widely distributed. It is known to occur at many points in New York within an area 9,000 to 10,000 square miles in extent, single beds of it being locally 40 to 80 feet in thickness. Several beds of it sometimes occur one above another, interstratified with other sorts of rock, and their aggregate thickness sometimes reaches as much as 100 feet. In some sections, therefore, the salt makes a very considerable fraction of the total thickness of the series. The same relations hold still farther west. Near Cleveland, four salt beds, 50 feet and less in thickness, are interstratified with 500 feet of shales belonging to this period.

The presence of salt beds in New York and Ohio indicates that during the movements which took place about the close of the Niagara period, great lagoons or inclosed seas were formed. In these lagoons it is believed the red shales and other formations of the Salina group were deposited. Had the climate of the region been as moist as that of the present time, these lagoons would hardly have become abnormally saline. The fact that salt was precipitated in such quantities is therefore an indication of aridity. Data are not at hand for determining whether the aridity was local or general. Whenever and whereever the water of these inclosed seas reached the saturation-point for salt, its precipitation began. Occasional incursions of the sea, bringing in new supplies of salt water, followed by periods when the lagoons were cut off from the sea, and suffered rapid evaporation, would seem to meet the conditions demanded for the formation of the salt. So also would a slight continuous connection with the sea, such that the inflow of sea-water into the basin did not balance the excess of evaporation over precipitation in the basin area. Beds of salt 40 to 80 feet thick imply the evaporation of 3000 to 6000 feet of normal sea-water.

It is not known how nearly continuous the beds of salt are in the area within which they occur. Knowledge concerning them is obtained only from borings, for they are buried beneath great thicknesses of younger rock. Since the strata dip to the south, the salt beds lie farther and farther beneath the surface in that direction. Much of the salt of commerce which comes from New York is not derived immediately from the salt beds, but from the waters of salt wells. The water of these wells probably became briny by passing over or through the salt beds, or over or through strata of shale through which salt is disseminated.

Gypsum is often associated with sedimentary formations deposited in inclosed seas. It is much less soluble in waters which are nearly saturated with salt than in sea-water. Since it is usually present in saline waters, it is likely to be precipitated as the water approaches the saturation point for salt. In keeping with these general facts, it is present in the Salina series. Some of the gypsum is probably of secondary origin, being the result of the reaction of sulphuric acid on calcium carbonate.

The limestone of the Salina proper is largely contemporaneous with the shales and salt beds. It is thickest where they are thin, and thin where they are thickest. It contains few fossils, and may be a chemical precipitate. Its relations to the shales and salt beds are such as to indicate that the areas of accumulation of the several sorts of rock material were shifted from time to time, as if by gentle changes of level of land or water.

The thickness of the beds of the Salina group is considerable, being about 1500 feet near Ithaca, and still more in the mountains of Pennsylvania, where it attains its maximum development, though free from salt. From central New York the formation thins both to the east and west.

The sequence of changes in the Salina region of New York is indicated by the following table:[1]

Decreasing Salinity.	H G	Niagara-Guelph fauna	Cobleskill
	F	Waterlime with Eurypterus	Salina
	E	Gypseous shales	
Increasing Salinity.		Beds of rock salt	
	D	Gypseous shales	
	C	Pittsford shale with Eurypterus	
	B	Guelph fauna	Niagaran
	A	Niagara (Lockport) fauna	

Associated formations.—Above the Salina proper of New York, there is a thin (150 feet maximum) formation of limestone, the Waterlime (Cobleskill, Rondout, Manlius, etc.), which is generally regarded as a part of the Silurian system. The name Waterlime has reference to the fact that the limestone is the source of hydraulic cement, though it is by no means everywhere useful for this purpose, and many other limestone formations are similarly used. The Waterlime is more wide-spread than the Salina, extending westward through Ohio (where it is often shaly) to Indiana (Kokomo) and to Wisconsin. Both its distribution and its character show that the eastern interior was again more generally submerged than during the deposition of the salt-bearing series which preceded. In the Waterlime group, especially its lower portion (Cobleskill), the Niagara-Guelph fauna reappears (see p. 386), indicating a return of marine conditions, and of a fauna which had been excluded for a time from this region because of the salinity of the waters. The sequence of conditions during the Salina is shown diagrammatically above, and the relations of the Silurian and Early Devonian formations on opposite sides of the barrier which separated eastern from central New York, are suggested by Fig. 182.

[1] Hartnagel, Bull. 69, N. Y. State Museum, p. 1159.

Silurian in the West.

The Silurian and Ordovician systems have been usually mapped as one under the former name in the area west of the Great Plains. At various points in this region there is, between the Ordovician below and the Devonian above, a series of sedimentary beds poor in fossils. The character of the fossils being indecisive, the age of the beds has not been certainly determined. Some of them may be Silurian, though in many regions all appear to be referable to the Ordovician. If they are to be correlated with the Silurian, the Ordovician types of life may have lingered on in the west much longer than in the east. If the Silurian is really absent from all the areas where its presence is not known, it would appear that a large part of western North America was land during the Silurian period. The Silurian system has not been identified in the fine sections of the Colorado canyon in Arizona, and probably does not exist there. This may mean that either this part of the west was land during the Silurian period, or that such Silurian formations as were deposited here were subsequently removed by erosion during an interval of emergence. Silurian beds are reported from the Fort Apache region of Arizona,[1] from southern California and Nevada,[2] and from the Seward Peninsula of Alaska.[3] They are doubtfully reported from the Canadian Rockies, but the beds in question seem to belong to the same system as many other western beds, referred tentatively to the Ordovician on the basis of their fossils.[4]

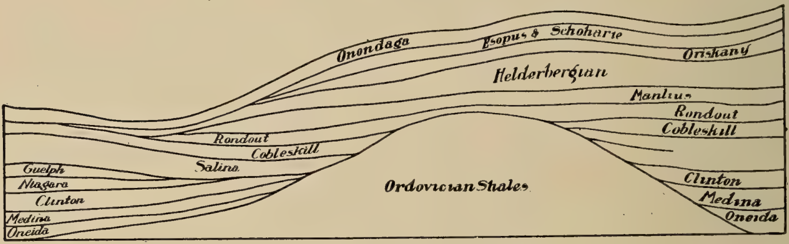

Fig. 182.—Diagram showing overlaps and succession of formations of the eastern interior sea during the Silurian and Early Devonian periods (Hartnagel.)

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[1] Reagan, Am. Geol., Vol. 32, 1903, p. 278.

[2] Spurr, Bull. 208, U. S. Geol. Surv., pp. 70, 86, and 202.

[3] Collier, Professional Paper No. 2, U. S. Geol. Surv.

[4] Dawson, Bull. Geol. Soc. Am., Vol. 12, p. 68.

The Helderberg formation.—It has been customary in the past to regard the Helderberg formation as a part of the Silurian system, though its reference to the Devonian has often been suggested. The fossils of the Helderberg formation are commonly regarded as pointing to alliance with the Devonian faunas, rather than with the Silurian.[1] By this standard, therefore, the reference of the Helderberg formation to the Devonian system seems the more appropriate.

SUMMARY

As in the case of all preceding systems of the Paleozoic, the greater thicknesses of Silurian strata occur in the Appalachian mountain system. Here the Medina and Oneida have a thickness of 1500 feet, the Clinton of 2000 feet, and the Niagara and Salina of 1500 feet (central New York), giving the Silurian system a thickness of about a mile, though this is far more than its average. In Maryland its thickness is between 2000 and 2500 feet. It is chiefly clastic below, with limestone above.[2] Over the interior, the system is relatively thin, being measured by hundreds of feet rather than by thousands. In keeping with these variations in thickness, the Silurian along the Appalachian belt is largely of clastic sediments of shallow-water origin, while that of the interior originated in clear, though not necessarily deep water. During most, if not all, the period, the Appalachian trough was shut off from free communication with the interior sea, but connected with the Atlantic, perhaps by way of the present Chesapeake region. The great thicknesses of strata in the eastern mountain region were deposited in this Appalachian trough. Since all or most of them were deposited in shallow water, they are usually thought to point to the conclusion that the trough was sinking, and that at a rate comparable to that at which the sediments accumulated. This view may, however, need to be qualified by considerations such as those suggested on page 257. So far as local sinking took place, the accumulation itself, as already suggested, may have been the cause, or one of the causes, of the subsidence. Coincident with the downward warping of the trough, the adjacent land area which supplied the sediments, was probably warping upward steadily or periodically.

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[1] Clarke, Review of the Hercynian fauna, 42d Rept. N. Y. State Mus., p. 408. See also views of Tschernychew, Am. Geol., Vol. XIV, 1894, p. 119; Schuchert, Bull. Geol. Soc. Am., Vol. II, pp. 241–332; Williams (who advocates the opposite view), *idem*, pp. 338–346; and Kayser, Geologische Formationskunde, zweite Auflage.

[2] Prosser, Jour. of Geol., Vol. IX, pp. 410–15.

The history of the Silurian period, as now understood, involves, (1) a general submergence of the eastern part of the United States west of Appalachia, by which the sea became more and more wide-spread until the close of the Niagara epoch; (2) a partial withdrawal of the sea from the same area during the Salina epoch; and (3) a possible extension of the sea at the close of the Salina epoch. There were doubtless many minor oscillations of level not distinctly recorded in the rocks, or, at any rate, not yet distinctly determined.

Of the sediments deposited along the Atlantic coast on the eastern border of Appalachia during the Silurian period little is known. They have not been identified at any point within the present land area south of New England. From this it is inferred that the Silurian shore south of New England was farther east than that of to-day, and that the Trans-Appalachian Silurian strata are still beneath the sea, deeply buried by younger formations. There is no certain knowledge, however, that the Silurian seas did not cover some part of the present land area east of the mountains. If so, such formations as were made have been removed by erosion, or transformed by metamorphism so that they have not been recognized, or lie buried beneath later formations. Farther north, as in New England and beyond, the sediments of this period seem to have accumulated partly in bays which affected the coast, and partly along the border of the open sea.

Outcrops.—The principal areas where the Niagaran series appears at the surface are shown on the map, Fig. 174. A map showing the outcrop of the system as a whole would not be very different (see Plate I). Fig. 174 shows also the relations of the Silurian to older systems, and hazards a conjecture as to their probable occurrence where now concealed. The principles underlying the distribution of outcrops have already been discussed (p. 252 *et seq.*).

Former extent and general stratigraphy.—The present margins of the several Silurian formations are not their original margins, for their exposed parts have suffered erosion, and the erosion of dipping beds, as already explained, shifts their outcrops. In some localities there are certain reliable data for estimating the former extension of the formations. In Wisconsin, for example, remnants (outliers, *a*, *b*, *c*) of the Niagara are found far beyond the main body (*S*, Fig. 183) of

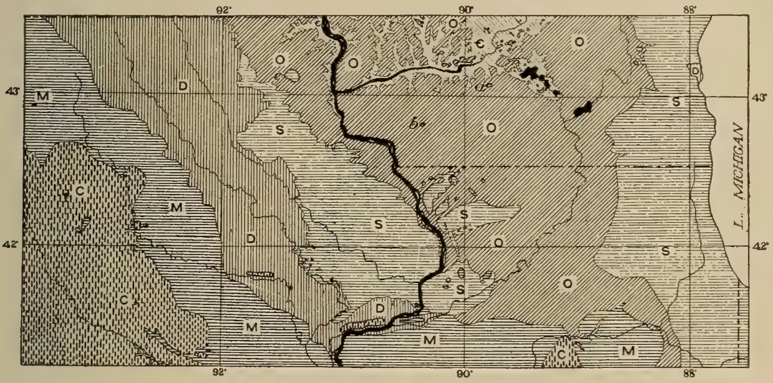

FIG. 183.—Map showing the surface distribution of Silurian, Ordovician, and other formations in southern Wisconsin, northern Illinois, and eastern Iowa. Є = Cambrian; *O* = Ordovician; *S* = Niagara, and *a*, *b*, *c* are outliers of *S*; *M* = Mississippian; and *C* = Carboniferous.

the formation as it now exists. These remnants fix at least a minimum limit to the original extension of the formation. The stratigraphical relations are indicated by the accompanying section (Fig. 184), which

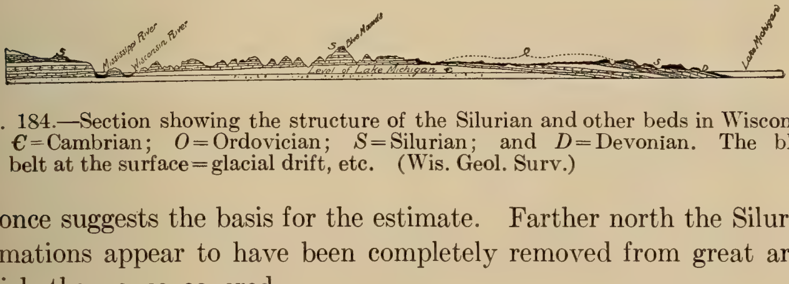

FIG. 184.—Section showing the structure of the Silurian and other beds in Wisconsin. Є = Cambrian; *O* = Ordovician; *S* = Silurian; and *D* = Devonian. The black belt at the surface = glacial drift, etc. (Wis. Geol. Surv.)

at once suggests the basis for the estimate. Farther north the Silurian formations appear to have been completely removed from great areas which they once covered.

The map (Fig. 185) of a part of New York shows the relations of the outcrops of the several Silurian formations in the western part of that State. Their former northward extension can only be conjectured, but it was probably considerable. Fig. 186 shows the stratigraphic relations of the beds shown on the map, the section being from north to south. Figs. 184 and 186 fairly illustrate the stratigraphic relations of the Silurian in the interior generally. Their stratigraphic relations in the Appalachian mountains are illustrated by Figs. 138 and 139, where the upper part of the formation marked *S* is often Silurian (the lower part being Ordovician).

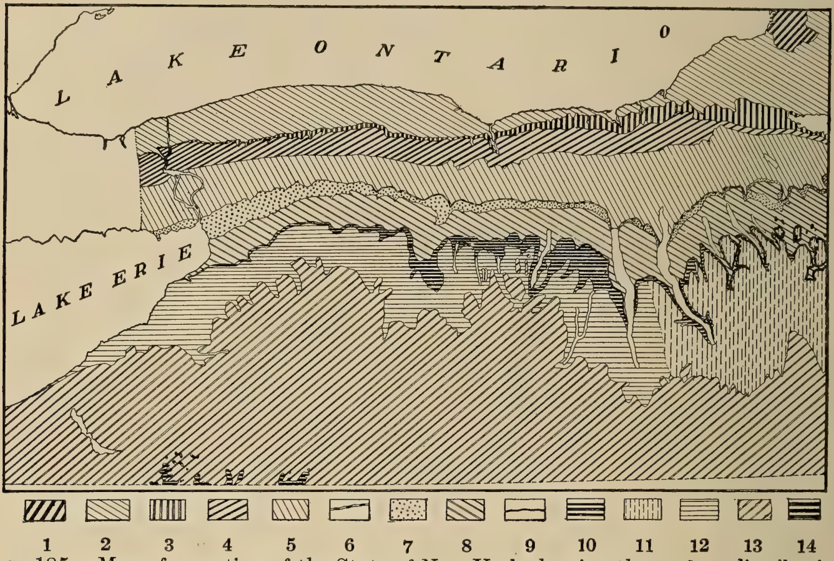

Fig. 185.—Map of a portion of the State of New York showing the surface distribution of the various Silurian and Devonian formations. 1 = Ordovician; 2 to 5 = Silurian; 6 to 13 = Devonian; 14 = Mississippian.

Sections of the Silurian in various regions are given on pp. 317–320, and in the Appendix, Vol. III.

Igneous rocks.—At few points in North America have igneous rocks of Silurian age been identified. The Silurian formations are sometimes affected by igneous intrusions, but the date of the intrusions is generally uncertain. Some of the igneous rocks of New Brunswick are thought to be of Silurian age, and perhaps some of those of Nova Scotia

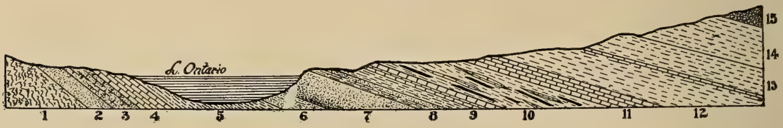

Fig. 186.—Section showing the structure of Silurian and Devonian beds in western New York. 1 = Pre-Cambrian; 2 = Cambrian (Potsdam); 3 to 6 = Ordovician, Calciferous, Trenton, Utica, and Hudson River respectively; 7 to 10 = Silurian, Oneida and Medina, Clinton, Niagara, and Salina respectively; 11 to 14 = Devonian, Helderberg, Hamilton, Genesee, Portage, Catskill, and Chemung respectively; and 15 = Carboniferous.

and Maine.[1] In the Fox Islands of Maine, the Niagaran age of some igneous rocks seems to be clearly indicated.[2]

CLOSE OF THE SILURIAN.

The closing stages of the Silurian were marked by the withdrawal of the epicontinental sea from considerable areas of the eastern interior which had been submerged during the Niagaran. The sea appears to have continued to cover the area of the Appalachian trough. Orogenic disturbances at this time seem to have been essentially wanting in North America. The geographic changes at the close of the Silurian appear to have been greater than those which occurred during the period, dividing it into epochs and stages, but they were notably less than those which closed the Ordovician. It follows that the Silurian system is less distinctly separated from the Devonian above than from the Ordovician beneath.

FOREIGN SILURIAN.

In Europe the Silurian strata have a distribution similar to that of the Ordovician, though they are wanting in some regions where the latter are present. As in the Cambrian and Ordovician periods, the continent seems to have been divided into two distinct geographic provinces. Within the northern, the Silurian strata are rather less widely distributed than those of the preceding system, especially in eastern and northeastern Russia. The fact that the Silurian strata do not appear at the surface over wide areas does not indicate their general absence so much as their widespread concealment. They are believed to be widely distributed beneath the younger beds between the Baltic and the Urals, as well as farther east. In most of the northern province, outside of Britain the system has been little deformed.

In the southern province, the Silurian formations are not widely exposed, appearing in small areas only amidst formations of lesser age. In contrast with the Silurian rocks of the northern province, those of the southern are much deformed.

The Silurian (the name comes from the name of an ancient tribe of Britain, the *Silures*) formations of Europe, especially of the northern province, are more largely composed of limestone than those of the Ordovician, suggesting clearer seas. In Great Britain, the three principal groups of the system, commencing below, are (1) the Llandovery, (2) the Wenlock, and (3) the Ludlow.

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[1] Williams, H. S. Jour. of Geol., Vol. II, pp. 16–18.

[2] Smith, G. O. Geol. of the Fox Islands, Me., Rev. Am. Geol., Vol. XIX, p. 214

In general the Silurian rests conformably on the Ordovician, but this is not true in the British Isles, where the younger system rests on the upturned and eroded strata of the older. As in America, the system contains little igneous rock.

Its thickness is less than that of either of the two preceding systems, being but 3000 to 5000 feet in Great Britain. It is perhaps needless to add that this lesser thickness does not necessarily denote a shorter period of time. It may equally well stand for a less rapid rate of accumulation.

The Ordovician and Silurian of other continents have not been generally distinguished. The equivalents of the two systems as distinguished in Europe and North America probably occur in all the less well-known continents. Strangely enough, the faunal resemblance of the Silurian of other regions, even of other continents, to that of the northern province of Europe, is stronger than that of this province to the southern province of the same continent.

CLIMATE.[1]

There is nothing to indicate great diversity of temperature in the Silurian period, and much to suggest that its uniformity extended through great ranges of latitude, for the fossils of warm-temperate latitudes are in part the same as those in Arctic regions. Certain regions (New York and vicinity) appear to have been temporarily (Salina epoch) arid.

THE SILURIAN LIFE.

The extensive withdrawal of the sea from the surface of the North American Continent at the close of the Ordovician period very greatly reduced the area of shallow water available for the forms of life that had so richly peopled it during that period. A repressive evolution of much severity necessarily followed. This constitutes the great biological feature of the transition from the Ordovician to the Silurian. With the extensive re-invasion of the interior by the Mid-Silurian

[1] Schwarz, Jour. Geol., 1906.

sea, there followed an expansional evolution of the shallow-water fauna, and this constitutes the great biological feature of the middle of the period. Toward the close of the period there was another but less considerable restriction of the epicontinental sea, complicated with intense salinity in the eastern interior region, and there followed a second repressive evolution marked by special features. Through this, the fauna passed into the Devonian type, and the marine life-history of the Silurian was closed.

These major biological movements were varied and complicated by many minor movements upon which we cannot dwell. These generalizations relate solely to the shallow-water marine life. The history of the land life should theoretically have been the reciprocal of that of the sea; for as the sea contracted the land expanded, and an expansional evolution of land life should have run hand in hand with the restrictional evolution of the sea life. This was probably the fact, but the record of the land life is too meager to demonstrate it.

It is not probable that the life of the ocean surface or of the abysmal depths was sensibly changed by these continental modifications, but there is practically no evidence bearing on this point, for, as ever to be borne in mind, the geological record of marine life is almost wholly that of the shore tracts and the epicontinental seas.

Had the physical changes of the continent at the close of the Silurian period been as pronounced as those at its beginning, it would have constituted an ideal cycle, consisting of an advance, a dominance, and a retreat of the sea, attended by expansional, cosmopolitan, and restrictional phases of shallow-water life, and would thus have rounded out a typical period. Starting with a transformed remnant of the previous fauna distributed along a skirting shoal tract and gathered in a few bordering embayments which harbored it during the vicissitudes of the transition, the life expanded with the expanding epicontinental seas, attained a cosmopolitan prevalence in the Mid-Silurian, and later, with the retraction of the sea, shrank again to meager proportions and was transformed into the initiative fauna of the next period.

The Transition from the Ordovician.

Severely restricted as the shallow-water life must have been during the stage of the greatest sea withdrawal, the record probably makes it appear more impoverished than it really was. The shore tracts were then far out on the borders of the continental platform, and the deposits there made were buried beneath later deposits when the sea readvanced, and have been specially subject to further burial by subsequent border deposits. Large portions of these tracts are probably now under the sea. They are, therefore, of all epicontinental deposits least accessible to observation.

Aside from the lessened area, the life conditions were probably less favorable, area for area, than in the stage of sea expansion, for the wash from the land was presumably augmented by the increased land area and the greater relief of the land caused by the lowering of the sea-level, if not also, as is probable, by the upward bowing of the continental surface. The increased detritus poured by the rivers into the coast belt probably inhibited some forms of life, injured others, and helped but a few. Some of the basins or embayments were doubtless affected by too great freshness of water and some by too great salinity, and what was probably more unfavorable for life, by alternations from the one to the other.

These general characterizations find exemplification in the meagerness of the faunas of the Shawangunk grit, the Oneida conglomerate, and the Medina sandstone, all of which are very barren of fossils. Granting that some part of this barrenness may be due to the dissolving away of relics once contained in the beds, there can be little doubt of an original barrenness, for whatever may be true of the coarse sandstones, there is no reason to assume exceptional solution of organic substances in the abundant shales and fine-grained argillaceous sandstones.

In the earliest beds referred to the Medina in the eastern interior, there are a few lingering Ordovician species. Then follows the great mass of the Medina formation in which practically no determinable life relics appear, while near the top of the deposit a meager fauna of the post-transition type initiates the distinctive Silurian fauna. Scarcely more than a dozen species of invertebrates have been identified, and these have a pauperitic aspect that seems to tell of the hard conditions under which they lived. The very fact that the Medina shales and sandstones are prevailingly red, probably tells a tale of hostility to life, but we cannot read it with much assurance at present.

It will claim consideration in connection with the great red deposits of later periods.

Universally adverse conditions are not, however, to be assumed during the transition epoch. The very drawing down of the waters on the borders of the continent must inevitably have so shallowed the sea on some deeply submerged tracts as to have made them congenial ground for the retreating faunas of the interior. This might well be true of deep embayments on the continental border. The Gulf of St. Lawrence seems to have been a notable example, and to have constituted a harbor of refuge for the retiring hosts of the interior. In it, as shown by the deposits of Anticosti, Ordovician species lived on for varying lengths of time and mingled with Silurian species as they developed, and so recorded the transition. This appears to have been the breeding-ground of one of the provincial phases of the Silurian fauna, but it is not at all probable that it was the only one. Doubtless there were other similar embayments, and the whole coast tract probably made its contribution to the Silurian fauna; but south of the St. Lawrence the record of the phases of life transitional from Ordovician to Silurian is not at command. The main Silurian fauna of the interior apparently did not arise from that of the St. Lawrence embayment or of the Atlantic border, but developed somewhere at the north, or came in from the eastern continent.

The Expansional Stage and the Mid-Silurian Fauna.

As the sea slowly crept out upon the face of the continent toward the middle of the period, increasing room and more congenial conditions for most forms of shallow-water life afforded the means of a new expansional evolution, and this finds expression in the Niagaran fauna. This is comparable to the expansional stage of the Mid-Ordovician fauna. The families and classes remained nearly the same as in Ordovician time, but the majority of the genera were new, as were nearly all the species. A very few species of extraordinary longevity bridge the great interval, such as *Leptæna rhomboidalis* (Fig. 163, *w*), *Plectambonites sericeus* (Fig. 163, *x*), and *Platystrophia biforata*. These stand out as conspicuous examples of extraordinary persistence, though even they had changed somewhat. In general there was a biological advance, but regarding the particular classes, some had risen and some had fallen, while all had undergone a change. The more conspicuous features of these changes claim attention.

Echinoderms: the blastoids.—A distinguishing feature of the Silurian fauna was the rich and varied development of the echinoderms, involving at once the rise or the decline of old forms and the introduction of new ones. To the five classes present in the Ordovician, there was now added the blastoids, and the full list of classes adapted to fossilization was completed. The new class consisted of symmetrical, bud-like forms, with a calyx of a definite number of plates, very regularly and beautifully arranged in pentamerous order, but without true arms, as shown in Fig. 187, *i*. Only two genera of blastoids, so far as known, were as yet present, but in the two succeeding periods a rapid development was achieved, followed by a swift decline.

The rise of the crinoids.—The appearance of the blastoids was a mark of advance; but the dominant feature was the rise of the crinoids. They attained such abundance in certain congenial localities that their fragments formed the main substance of the limestone. These spots became veritable "flower-beds" of "stone lilies," and certain localities, as Lockport, N. Y., Waldron and St. Paul, Ind., Racine, Wis., Chicago, Ill., Gotland, Sweden, and Dudley, England, have become noted as peculiarly rich crinoidal fields, where beautiful and varied forms grew in groves, as it were. The assemblage of species at each of these noted localities had its own peculiarities, but the genera were usually much the same. A few Silurian crinoids are shown in Fig. 187, *a*, *b*, *c*, *d*, *e*, but no such limited selection of figures can do justice to the variety and beauty of form they displayed.[1] The wide differences of those illustrated, however, gives some hint of the development of the class. Among the notable features was a large projecting tube whose apparent function was to carry the used waters of the body cavity away for discharge at a distance from the food grooves, with an apparent hygienic purpose. In certain cases, this tube was curiously expanded above, the plates spreading into a broad umbrella-like canopy with the apparent purpose of still more effectively preventing the mingling of the used and unused water. A new feature was the consolidation of the plates at the base of the calyx, imparting added strength to it. Spines were occasional features and doubtless served a defensive purpose. Some species were notably ornamented by various figures upon the exterior of the plates, the function of which can only be conjectured. The arms of the camerate crinoids, which, in Ordovician times, were largely formed of a single series of plates, nearly all came to have a double series in the Silurian. Notwithstanding these and other expressions of progress, there remained many remnants of the more primitive characters, indicating that the class had not yet reached its structural climax. The lower orders of the class were still present, but in diminished numbers. The decline of these and the rise of the higher types is in itself a mark of progress. At the same time, the continued existence of the lower types teaches that the introduction of the higher was not at once fatal to the welfare of the lower.

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[1] For a fine series of illustrations see the classic work of Wachsmuth & Springer, The North American Crinoidea Camerata, Mus. Comp. Zool., Cambridge, Mass., Vol XXI, 1897.

The cystoids.—Though the cystoids passed their climax in the Ordovician, they continued to be abundant in the Silurian, and many attained larger sizes than are known to have been reached before. They show in some phases a tendency to greater regularity in the arrangement of the plates, as though even they felt the influence of the causes that made for order and symmetry, so well expressed in the crinoids and blastoids; but on the whole, irregularity continued to characterize them (Fig. 187, *f*, *g* and *h*).

Other echinoderms.—The starfishes appear to have made little progress and to have had no large place in the fauna; the serpent stars and the echinoids had even less. It is important to note these slow developments of types that came to be prominent very much later, for it possibly represents a general fact, viz., that great classes were really slow in their evolution, however suddenly they may seem to have come into existence. It is not impossible that the ascents of the cystoids and crinoids to their climaxes would be found equally as prolonged as those of their kin if we could trace them back through their full histories. Just a little greater imperfection in the record would have eliminated all trace of the ophiuroids and echinoids in these early periods and would have made their appearance in abundance at a later period seem sudden and remarkable. This suggestion is not to be accepted as an affirmation, for there are some strong grounds for believing that evolution was sometimes really rapid relatively.

The continued importance of the brachiopods.—The brachiopods

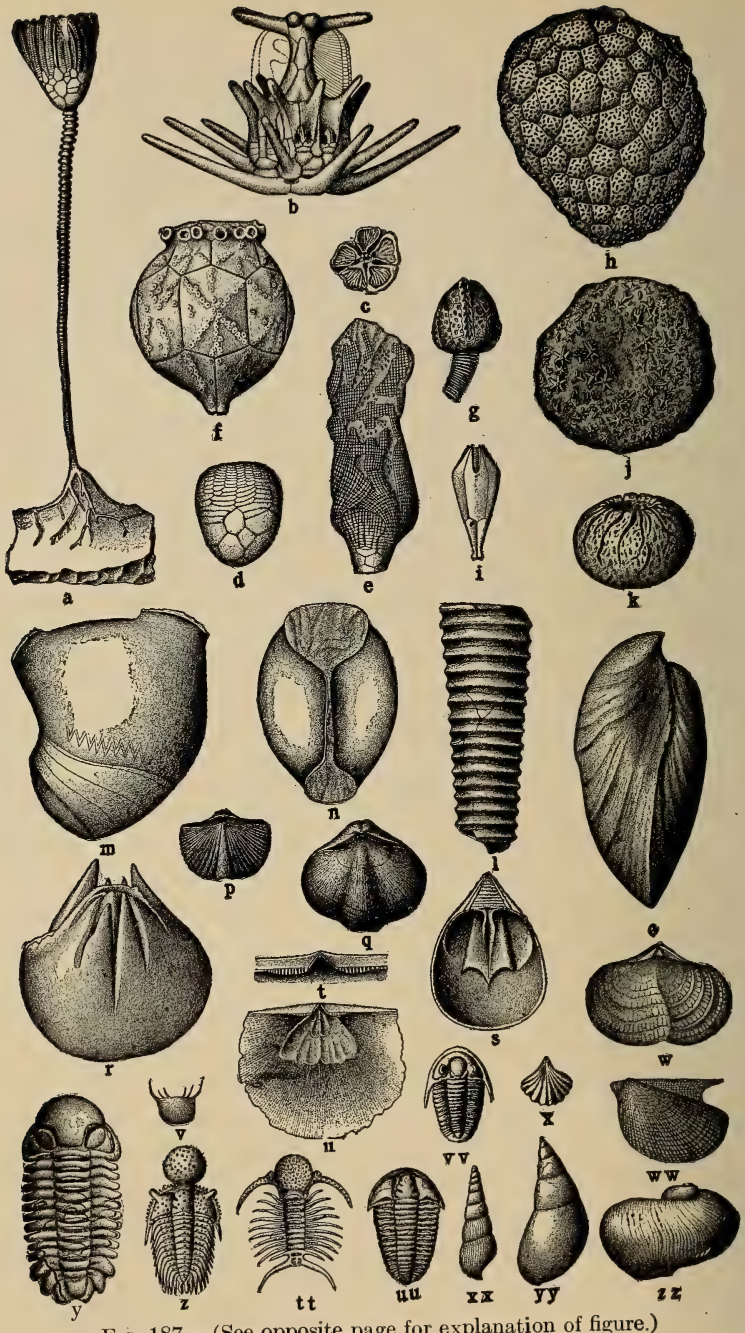

FIG. 187.—(See opposite page for explanation of figure.)

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EXPLANATION OF FIG. 187.—*Crinoidea: a, Eucalyptocrinus crassus* Hall, a complete crinoid, showing root, stem, and body; *b, Callicrinus murchisonianus* Ang., showing extraordinary spinose ornamentation; *c, Petalocrinus mirabilis* Weller, showing a remarkable type of arm differentiation, the arms being consolidated into five triangular plate-like bodies; *d, Lecanocrinus macropetalus* Hall, one of the articulate crinoids; *e, Crotalocrinus pulcher* (His.), a crinoid with remarkably differentiated arms. *Cystoidea: f, Caryocrinus ornatus* Say., a cystoid with regularly arranged body-plates; the pores may be seen arranged in radiating lines from the centres of the plates; *g, Callicystis jewetti* Hall, a cystoid with unsymmetrical arrangement of plates, the arm furrows recumbent, the pores arranged in groups; *h, Holocystites adiapatus* Miller, a cystoid with irregularly arranged plates and scattered pores. *Blastoidea: i, Troostocrinus reinwardtii* (Troost), showing the typical bud-shaped form of these organisms. *Sponges: j, Astræospongia meniscus* Roem., a saucer-shaped sponge with exceptionally large spicules; *k, Astylospongia præmorsa* (Goldf.), a globular sponge showing the osculum above and the ends of the water canals. *Cephalopoda: l, Orthoceras annulatum* Sow., a straight chambered shell with annulations; *m–n, Phragmoceras nestor* Hall, lateral and end views of a curved chambered shell with peculiar constricted aperture. *Brachiopoda: o, Pentamerus oblongus* Murch., lateral view of an internal cast; *p, Spirifer niagarensis* (Con.), exterior view of the brachial or dorsal valve, with the cardinal area and beak of the pedicle or ventral valve showing above; *q, Spirifer radiatus* Sow., a view similar to the last. These two figures show the plicated and non-plicated spirifer shells, marked with fine radiating striæ; *r, Trimerella ohioensis* Meek, the internal cast of a highly differentiated inarticulate brachiopod, showing the finger-like casts of the excavations beneath the elevated muscular platforms; *s, Trimerella acuminata* Bill., the interior view of a pedicle or ventral valve, showing the elevated platform for muscular attachment, excavated beneath; *t, u, Stropheodonta profunda* Hall, interior of the pedicle or ventral valve, showing muscular impressions, cardinal area, delthyrium, and crenulated hinge line, with an enlarged view of the area and hinge; *v, Chonetes cornutus* (Hall), exterior view of pedicle or ventral valve, showing the cardinal spines; *w, Streptis grayi* (Dav.), exterior view of the brachial or dorsal valve, showing the cardinal area and beak of the opposite valve and the peculiar twisted form of the shell; *x, Rhynchotreta cuneata* (Dal.), exterior view of the brachial or dorsal valve, showing the beak and pedicle opening of the opposite valve. *Trilobita: y, Sphærexochus mirus* Bey., dorsal view; *z, Staurocephalus murchisoni* Barr, dorsal view, showing the peculiar globular anterior prolongation of the head; *tt, Deiphon forbesi* Barr, dorsal view of a peculiar trilobite having the pleural lobes much reduced; *uu, Calymene niagarensis* Hall, dorsal view of one of the commonest Silurian trilobites; *vv, Cyphaspis christyi* Hall, dorsal view. *Pelecypoda: ww, Pterinea emacerata* (Con.), exterior view of the left valve. *Gastropoda: xx, Loxonema leda* Hall; *yy, Subulites ventricosus* Hall; *zz, Platyostoma niagarensis* Hall, views of three types of Silurian coiled shells. (Weller.)

(Page 403)

stood the vicissitudes of the passage from the Ordovician to the Silurian with no loss to the prestige of the class, though they suffered an almost entire change of species and a very large change of genera. When it is considered that the brachiopods were among the most resistant and conservative of the invertebrates, this large change of species and genera emphasizes the stress of the conditions that controlled the transition, as well as the biologic importance of the interval of transition.

The brachiopods remained the most abundant organisms of the Mid-Silurian fauna, and shared with the crinoids, corals, and cephalopods the leading places. They had gained greatly in differentiation, and had made some notable advances in structure. On the whole they were more robust and gave more obvious signs of abundant vitality than in preceding periods. The curious concavo-convex forms were less abundant, though not wanting. There was a great increase in the spire-bearing genera. One of these, the *Spirifer*, named from its fine brachial spires, is especially interesting. It had acquired a double provision against the forcing of its shell by developing a long hinge line at the back and a strong interlocking fold and sinus at the front, and, in addition, its biconvex shell was usually, though not always, well plicated (Fig. 187, *p*). The hinge line was not very greatly extended during the Silurian period, but became remarkably elongate in the Devonian. The *Spirifers* appeared first in this period, but had their greatest development in the two periods following.

It is interesting to note that along with the progressive developments there were retrogressive modifications. Most of the brachiopods were mounted upon or attached by a pedicle which, while fixing them to the bottom or to some object, gave them some degree of freedom. But the *Crania* lost the functional use of the pedicel at an early stage in the individual's life, and became cemented to other shells, or some like object, thus losing their freedom of motion. Notwithstanding this, the family was more abundant than in preceding periods, and the degenerate development was apparently advantageous.

Among the beaked shells, the *Pentamerus* family became the most conspicuous and characteristic type (and gave name to certain beds). The *Pentamerus oblongus* (Fig. 187, *o*) was the largest and one of the most common of the Silurian brachiopods. The *Pentamerus*, like the *Trimerella* (Fig. 187, *r*, *s*), developed remarkable processes on the interior of the shell for the apparent purpose of shortening the muscles and giving them better attachment, and also to better adapt the interior to the visceral parts. Similar structural devices appear in other families. This mode of securing economy or advantage appeared in Ordovician times, though it was then rare.

Three brachiopod species which survived the vicissitudes of the transition from the Ordovician have already been mentioned. In the St. Lawrence embayment, where there was less disruption of continuity, at least two other species passed from the earlier period to the middle of the later. In Europe, the transition seems to have been easier, and more species survived it.

The decline of the bryozoans.—The coral-like bryozoans contributed much less material to the Silurian limestones than to those of the preceding period. This was partly because the whole class had declined in abundance, and partly because the more massive coralline type had fallen off relatively, and was largely replaced by the more delicate reticulate forms, such as *Fenestella* (Fig. 188, *f* and *g*). This change was probably advantageous, since a given number of individuals arranged in such a plexus would compass a larger area of food supply than in the more crowded form of the massive type, and at the same time would not seriously sacrifice their connection with one another. The incrusting forms of bryozoans became common, and often covered entirely the shells of mollusks and brachiopods.

The continued dominance of the cephalopods.—Except as possibly rivaled or overmastered by the little-known vertebrates, the cephalopods remained the most powerful of the known inhabitants of the Silurian seas. The large straight orthoceratites were less prevalent than before, though still common, while the curved and coiled forms were more numerous. The orthoceratites were more varied in external markings, some remaining smooth, some being fluted longitudinally, and some being annulated by rounded rings or wavy lines (Fig. 187, *l*), while others, by a combination of longitudinal and transverse markings, developed a reticulate ornamentation. Curved forms were the most numerous, and fully coiled forms were common. These were ornamented externally like the straight forms, but they were still quite plain in comparison with the remarkable ornamentation which the coiled forms assumed in later times. The apertures of the cephalopod shells of the Ordovician were usually circular or oval, but in the

Silurian times they often became curiously constricted (Fig. 187, *m–n*). This appears to have been a protective device and implies that the creature, although a member of the dominant type, had aggressive foes. The device is noted chiefly in the rather small curved or coiled forms, and may signify no more than the attacks of superior cephalopods. It probably means increased slowness and inability to escape by flight, for the animal could hardly have used his locomotive organs to advantage through such constricted openings. The device did not long continue, and it doubtless proved but a poor advantage, and that for a brief season only when conditions were peculiar.

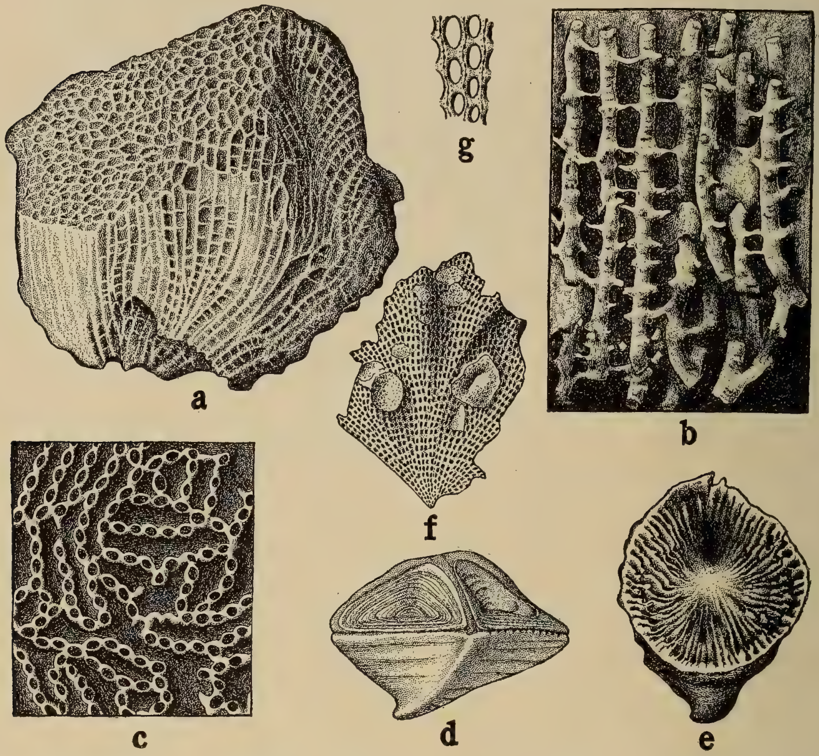

FIG. 188.—Corals: *a, Favosites occidens* Whit.; *b, Syringopora verticillata* Goldf.; *c, Halysites catenulatus* Linn.; *d, Goniophyllum pyramidale* (His.); *e, Zaphrentis umbonata* Roming. *Bryozoa: f, g, Fenestella parvulipora* Hall.

The slow advance of the gastropods and pelecypods.—Although the gastropods were fairly well represented in the Cambrian period, and quite amply in the Ordovician, they developed only a measured importance in the Silurian. They show advances in the preponderance of elevated spires, in increased variety of form, and often in their large sizes; but forms coiled in low spires, or in a plane, were still well represented (Fig. 187, *xx*, *yy*, *zz*). The pteropods were few, but the peculiar form *Conularia* was an interesting representative.

The pelecypods (Fig. 187, *ww*) were not as well represented in the Mid-Silurian beds as they were in the Ordovician, perhaps because the calcareous bottoms were less congenial to them. Some of the forms, however, were quite robust and displayed notable advances over previous forms.

Coral development and the inauguration of reef-building.—The prominence gained by the corals in suitable situations is one of the notable features of the Silurian fauna. In the Ordovician period the simple forms predominated over the compound. The ratio was now reversed, and the latter became very abundant. Among the notable types was the unique chain coral *Halysites* (Fig. 188, *c*), which was occasionally present in the Ordovician, but now became abundant; the honeycomb coral, *Favosites* (Fig. 188, *a*), accompanied by a group of allied genera; the organ-pipe coral, *Syringopora* (Fig. 188, *b*), and the cup coral, *Zaphrentis* (Fig. 188, *e*). A most peculiar coral of the simple class was *Goniophyllum* (Fig. 188, *d*), which instead of assuming the usual conical cup form took on a quadrangular shape and was provided with a cover (operculum) of four triangular plates hinged to the four sides of the cup's margin, so that when closed they formed a pyramid over the cup (Fig. 188, *d*; only two of the opercular plates shown). This was a protective device quite unknown among modern corals.

With their increase in abundance, the corals acquired the habit of associating themselves together, which resulted in the accumulation of coralline débris and the formation of reefs which, as they grew, rose above the common sea-bottom and secured the benefits of purer water and more active circulation. The known coral reefs appear to have stood some distance from shore, and to have been of the barrier type. Other life in great abundance and variety gathered upon or about these reefs, and they became rich depositories of the ancient faunas. The reef-forming habit appears to have been local rather than general, for over large tracts corals are found scattered in a markedly distributive fashion.

The initial decline of the trilobites.—No new families of trilobites, so far as known, were introduced during the period. Some new genera were added and many new species, but these did not offset the disappearance of old ones, and the class, though still important, may be regarded as having already entered upon its decline, so far as prevalence was concerned. This was not true apparently in respect to the rank of certain leading types, which continued to advance in organization. The highest Silurian forms were structurally equal, and perhaps superior, to any that preceded. The causes which induced the decline in numbers do not seem to have been incompatible with individual and generic progress. Singularly erratic developments of form attended the decline of the trilobites, some features of which are shown in Fig. 187, *y, z,* and *tt.* Less erratic types of trilobites are shown in Fig. 187, *uu, vv.*

Other crustaceans.—In addition to the trilobites, ostracodes were not uncommon, and their little bivalve shells are sometimes abundant as fossils. The ceratiocarids were also present. In view of the remarkable development of a distinctly crustacean fauna in the last stages of the period, the scantiness of these crustaceans in the Mid-Silurian epoch is notable.

Other marine invertebrates.—There was a most prolific field of sponges in western Tennessee, where the conditions were not only congenial to their growth but favorable to their preservation. The most abundant genus was *Astylospongia* (Fig. 187, *k*), a more or less spherical form characterized by notably grooved surfaces. A saucer-shaped form, *Astrœospongia meniscus* (Fig. 187, *j*), was also abundant.

Mr. G. F. Harris has recently found that sponges form the nuclei of chert nodules in the Chicago region. The genera *Astylospongia, Aulocopina,* and *Hindia* have been identified.

The peculiar *Receptaculites* family, whose zoological affinities were long in doubt, was still present, but chiefly represented by *Ischadites.*

The graptolites had lost much of the importance they possessed in Ordovician times, and in the course of the period approached extinction. Sea worms are recognized through their jaws, tracks, and burrows, and by the calcareous tubes which some of them secreted.

The scant record of the vertebrates.—In the earlier and Mid-Silurian deposits very few relics of fishes and fish-like organisms have been found, and these few are very imperfect. Near the close of the period, Silurian fishes were somewhat abundant and will be considered in connection with the closing Silurian fauna.

Marine plants.—Knowledge of marine plant life remains, as before, very unsatisfactory. While theoretically it must have been abundant, only obscure markings of the fucoidal type and a few evidences of higher forms have been found, and the interpretation of these is more or less doubtful.

Foreign Faunas and Migratory Relations.

Deferring the consideration of the peculiar closing fauna for a moment, the foreign relations of this rich and varied Mid-Silurian assemblage claim attention. The general progress of life on other continents, so far as known, was similar to that on the American, but perhaps less pronounced and symmetrical. A part of this similarity of progress was doubtless due to parallel evolution under similar general conditions, while a part was quite certainly due to intermigration Where the forms on different continents were merely similar, it is at present an open question whether the similarity was due to intermigration with modification or to independent evolution along similar lines; but where the forms on separate continents are specifically identical, especially if the species be peculiar and aberrant, it may safely be assumed that they had a common origin, and that migration is indicated. A striking case of this kind is presented by the quadrangular operculated coral *Goniophyllum pyramidale*, already mentioned (Fig. 188, *d*), which is found with identical idiosyncrasies in the island of Gothland in the Baltic Sea, and in Iowa. This evidence of migration is much strengthened by the presence in Gothland of three peculiar genera of crinoids that are also found in the upper Mississippi region. Besides such special cases, many prominent and familiar species were common to America and Europe, among which, neglecting the wide-ranging graptolites, were *Favosites gothlandica, Halysites catenulatus, Heliolites interstinctus, Dalmanella elegantula, Pentamerus oblongus, Spirifer radiatus, Rhynchotreta cuneata, Atrypa reticularis, Orthoceras annulatum, Homalonotus delphinocephalus,* and others. Some of these are also found in Asia, Australia, and New Zealand. Silurian genera occur in Bolivia, Peru, and Brazil, some species of which resemble North American and European species, but they have not been proved to be identical. Migratory connections in this case cannot be affirmed, but such connections with Europe, Asia, Australia, and New Zealand may be assumed as established. Since thirty or more species[1] are known to be common to North America and Europe (the interior of North America and Sweden and Great Britain), and since these embrace a wide range of genera of very different habits, there is a strong presumption of rather intimate relations. The lines of intercommunication therefore become matters of interest biologically and geographically.

The migratory route.—The most marked community of species is observed, not between the Atlantic border fauna of America and that of the opposite coast of Europe, but between the interior American fauna and that of Sweden and Great Britain. Singularly enough, it is the interior fauna that is pronouncedly intercontinental and cosmopolitan in character. It has already been stated that the interior sea seems to have had no free communication with the eastern and southern coast regions, and that an extension to the far west is doubtful, while to the northward a chain of deposits, now separated by erosion but probably once continuous, points to a broad thoroughfare in that direction (see map Fig. 174 and Fig. 190). This reaches to North Greenland, from which, by way of Spitzbergen, Nova Zembla, and North Russia to Gothland in the Baltic, the steps are not excessively great. The supposed connecting fauna has not, however, yet been identified in the imperfectly known Paleozoic beds of Spitzbergen, Nova Zembla, and North Russia. There is a possible alternative by way of the Iceland-Scotland submerged plateau, and still another alternative by way of the northwestern or Siberian route.

The paleontologic evidence favors a northern route, for the fauna of the Arctic islands contains many species common to the American interior province and the Swedish-English province. It is significant that the Mid-Silurian fauna of Sweden more closely resembles that of the American interior than it does that of New York. Relative to the assigned northern thoroughfare, the New York area was a side-gulf or embayment less readily reached by immigrants from the north than were the more open seas to the west. The very singular community of aspect recently shown to exist between the faunas of Gothland, Sweden, and Dudley, England, and the Iowa-Illinois-Wisconsin region give special emphasis to this.[2] *Crotalocrinus*, one of the most singular and highly specialized genera of crinoids, together with the genus *Corymbocrinus*, are common to the Gothland and the Chicago faunas. *Petalocrinus*, another highly specialized genus, is common to Gothland, Iowa, and Indiana. The peculiar little twisted brachiopod *Streptis*, of Europe, also occurs at Batesville, Ark., as do the peculiar trilobites *Deiphon* and *Staurocephalus*, which occur also at Chicago. The notable case of the square-topped operculated coral has already been mentioned. The presence of these several very peculiar and specialized forms at these localities on the two continents, taken in connection with the many less peculiar forms, clearly implies free intermigration and points with probability to the northern route.

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[1] Phillips, Man. Geol., Pt. II, 1885, p. 122.

[2] Weller, Jour. of Geol., Vol. IV, 1896, pp. 166–173, and Vol. VI, 1898, pp. 692–703.

The faunas that occupied the Appalachian trough, the St. Lawrence embayment, and the Atlantic coast appear to have had only indirect and limited connection with that of the interior during the earlier and Mid-Silurian epochs.[1] In the present state of knowledge, these bear the aspect of provincialism, as they have only a few species common to the great cosmopolitan fauna of north central America and northern Europe.

The Closing Restrictional Stage.

Following the luxuriant life of the Mid-Silurian epoch, there came, in North America at least, a very notable decline due to the withdrawal of the epicontinental waters from the larger part of the interior and to the conversion of the remainder into an excessively salt sea. In the deposits (Salina) of this sea almost no fossils are found The tract of excessively briny water appears to have formed a veritable "dead sea," though it was perhaps not absolutely devoid of life. This almost-lifeless sea was a peculiar and rather local development, and is to be regarded as a striking incident only in the more general restrictional movement. In addition to this special feature, the life evolution appears to have been affected by the partial replacement of the marine fauna by a fresh or brackish-water fauna, another unusual feature, at least one not before clearly recorded. It cannot be said, however, that this was certainly true, but it appears to us the better of the two interpretations that will presently be set forth. If this be correct, the rich marine fauna which prevailed so widely in the Mid-Silurian times suffered restriction in the closing Silurian stages not only to the extent of the increase of the land area, but also to the extent that sea-water was replaced by water bodies too salt or too fresh for the strictly marine life.

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[1] Ulrich & Schuchert, Rep. N. Y. St. Pal., 1901, pp 647–651. Weller, Geol Surv. N. J Pal., Vol. III, 1901, pp. 72–76.

The importance of recognizing the fresh-water or brackish-water faunas, if they really were such, lies in the fact that they did not constitute a relief or a resilience from the restrictional movement of the marine fauna, but intensified it. They were a feature of the reciprocal expansional evolution of the land life in the broader sense of that term which includes the life of the land waters as well as that of the land itself. The life of the land and land-waters expanded and contracted together in general, and in a phase opposite to that of the sea. The fauna which brings up this interesting question is that of the Waterlime to which we now turn.

The advent of a remarkable crustacean fauna.—The Waterlime beds represent a gradual return of the Salina basin to a condition hospitable to life. The fauna contained in these beds is limited, but most interesting and suggestive. In its dominant aspect it was a radical departure from that of Mid-Silurian stage, in that most of the familiar marine types were absent, while its signal feature was an abundance of large crustaceans of types barely represented before. The most characteristic of these were the great *Eurypterus* (Fig. 189, *a*) and the still more gigantic *Pterygotus* (Fig. 189, *b*). The former reached a length of one and a half feet or more, and the latter attained in the next period (Devonian), to which this stage was a transition, a length of over six feet. For crustaceans, these were truly gigantic dimensions, and were probably never surpassed. These giants among their kind seem clearly to have been aquatic forms, but whether they were primarily marine or fresh-water habitants is not so obvious. They are wholly extinct, and their habitat can only be inferred from their associations. Some crustacean fragments that seem to belong to the same subclass as the eurypterids (*Merostomata*) have been found by Walcott in Pre-Cambrian beds,[1] but their associates are too few to throw much light on this question, though they favor a marine habitat. A very few eurypterids appear in the Ordovician, where they are associated with marine invertebrates. In the Waterlime beds they are associated with ceratiocarids and ostracodes which are usually marine, and, very rarely, with certain brachiopods, which are marine. In the transition beds of England, Sweden, and Russia, the eurypterids are associated more freely with marine forms, but they are also associated with the seeds of land plants and with fish which, in the succeeding stage, seem to have occupied land waters chiefly. In the Devonian and Carboniferous periods, in which the eurypterids reached their climax and passed into their decline, and where they seem to have been in their more normal relations, they are associated with land plants, scorpions, insects, fishes, and fresh-water amphibians, which seem to imply a fresh-water habitat. In the light of these facts the more common inference has been that they were originally marine forms, and became adapted later to brackish and fresh-water conditions.[1] The alternative inference is that they were originally denizens of the land waters, and that their remains were occasionally and sometimes quite freely carried out to sea by streams, and were

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[1] Bull. Geol. Soc. Am., Vol. X, pp. 199–224, 1899.

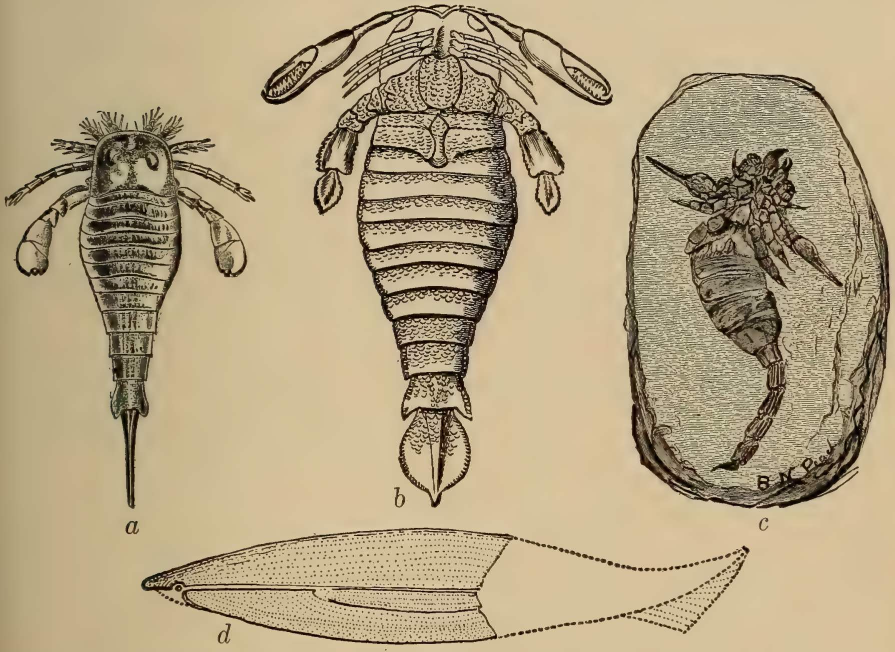

FIG. 189.—*a*, *Eurypterus fischeri* Eich., restoration after Schmidt; *b*, *Pterogotus anglicus* Agass., restoration after Woodward; *c*, *Palæophonus caledonicus* Hunter, after Peach; *d*, *Palæaspis americana* Claypole, restoration by Claypole, modified by Dean.

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[1] See Zittel's Text-book of Paleontology, Eastman's Translation, 1900, p. 673.

thus fossilized with marine forms. Their occasional presence in the earlier periods is thus explained, while their seemingly sudden appearance in abundance and in gigantic forms in the closing Silurian, and their prominence in the land-water deposits of the Devonian and Carboniferous finds ready explanation in the fact that these are the first well-preserved fossil-bearing deposits of land waters.[1] In these deposits the eurypterids often appear without any marine associates, while occasionally there are some marine or at least brackish-water forms associated with them, implying either that they lived in brackish or salt water at times, or that their remains were carried out into such waters by the land streams or estuarine currents.

These doubts as to the habitat of the eurypterids lend special interest to their fine development in the Waterlime beds from which mollusks, crinoids, corals, and similar marine forms are almost entirely absent. The few brachiopods found are usually pauperitic, as though they lived in uncongenial conditions. The occasional presence of a few undoubted marine forms does not so much indicate that the waters were habitually saline as merely that they were occasionally and partially so.

It is suggestive, in this connection, to note that these great crustaceans, appearing thus abruptly in the Waterlime deposits, are not found in the true marine beds that overlie the Waterlime, as might be expected if they were true marine types recently come into the seas, or into fossilizable form. It seems, therefore, rather more reasonable to regard their normal habitat as connected with the special conditions that prevailed during the Waterlime formation, than with the typical conditions of the sea. The Waterlime formation is universally regarded as representing a stage of emergence from the excessively salt Salina stage. Emergence from this stage might take either of two forms—(1) The connection of the basin with the sea might have become more ample, and the excessive saltiness of the water might be reduced by interchanging currents to the normal salinity of the sea. In this case the marine life should creep back into the region in proportion to its endurance of briny water, and the fauna should always be truly marine. (2) On the other hand, without any material change in the attitude of the surface or in its connections with the sea, the precipitation might be increased, or the evaporation lessened, or both, and as a result, the waters of the basin would become brackish and even quite fresh, where joined by streams, and would thus permit the introduction of a fresh-water fauna from the adjacent land waters. If, at the same time, the limited and perhaps intermittent connection with the sea still obtained, as it appears to have done during the Salina stage, there would also be some opportunity for the introduction of marine forms from the sea, especially at and near the points of such connection. The variations in the ratio of precipitation to evaporation might naturally lead to variations in the constitution of the water of the basin, and hence to conditions favorable to variation in the faunas, and to the mixing of those marine and fresh-water species that could stand the greatest variation in salinity. This latter interpretation is dynamically the simpler and seems to us the better to fit the fossil evidence.

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[1] On the Habitat of the Early Vertebrates, T. C. Chamberlin, Jour. Geol., Vol. VIII, 1900, pp. 400–412.

Eurypterids appeared prominently about this time in the faunas of certain beds in England, Wales, Scotland, Sweden, and Russia. In these regions there is no association with salt deposits, a fact which seems to imply that high salinity, as such, was not an essential condition. There, as in America, the eurypterids do not pass up into such of the overlying beds as are well stocked with marine fossils, although there is more or less association with certain marine forms. On the contrary, they seem to pass up into deposits of the "Old Red Sandstone" type, whose other fossils are chiefly land plants and fishes. In the Coal Measures of both continents similar eurypterids are found fossilized with numerous delicate ferns, as though they had been buried together in some quiet body of inland water. While these associations are not entirely decisive, they lend some notable strength to the inference that these large crustaceans were fresh- or brackish-water forms rather than true marine forms, and to the further inference that the peculiarities of the fauna of which they are a conspicuous factor were dependent upon the conditions of terrestrial or semi-terrestrial waters, rather than upon those of true sea-waters.

The appearance of scorpions.—It is at this time also that the earliest known scorpions appeared both in America (New York) and Europe (Scotland and Sweden). These were allied to the eurypterids, and their association lends something of force perhaps to the preceding considerations. The European forms have been thought to show

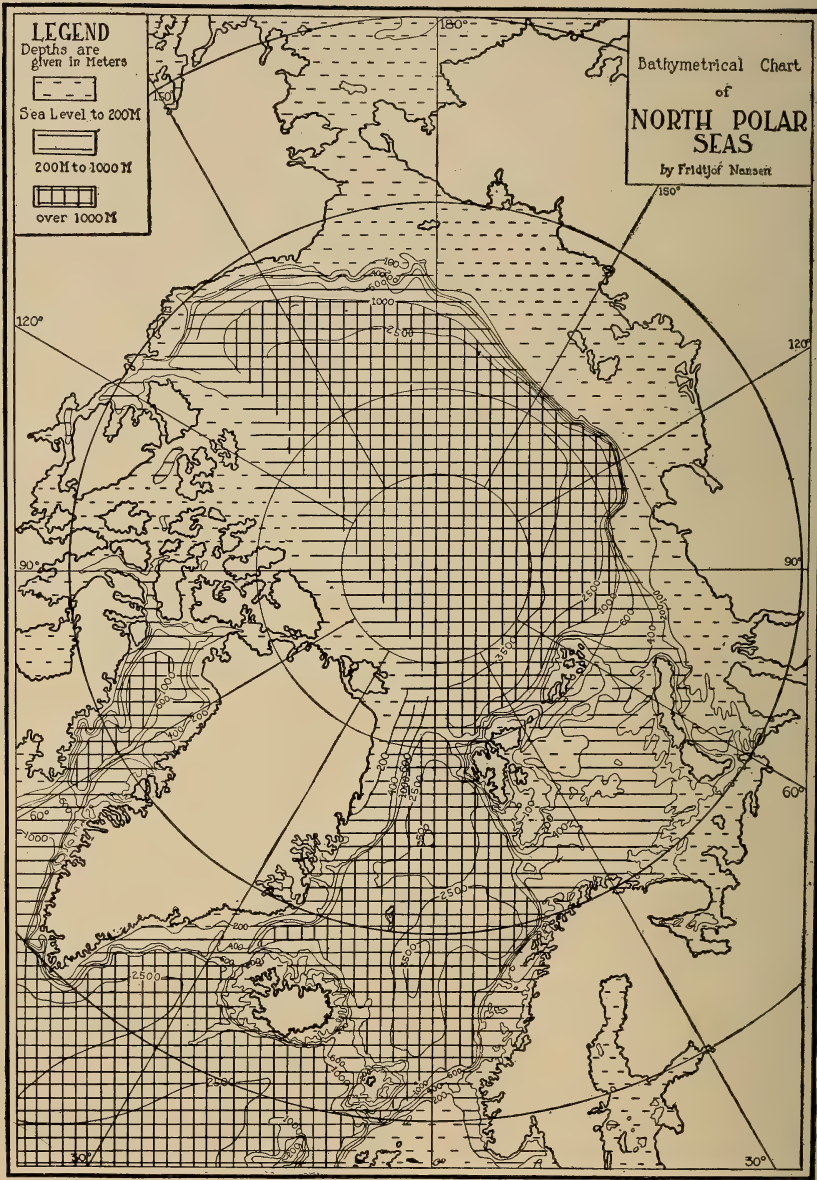

FIG. 190.—Bathymetric chart of the north polar seas, suggesting routes of migration for marine organisms. (After Nansen.)

breathing pores, and hence to be land species, as are the present forms, but this has been questioned. The sting and the poison glands have been identified, and the significant name *Palæophonus*, " ancient murderer," applied in consequence (Fig. 189, *c*). Whitfield, however, thinks that the American species may have been aquatic.

The presence of fishes.—The addition of fishes emphasizes the pecularities of this fauna. Except for their singular occurrence in Colorado in the Ordovician, fish remains have not been found in America until this stage. *Palæaspis americana* (Fig. 189, *d*), a low fish-like form referred to the ostracoderms, has been described by Claypole from Pennsylvania. In Europe a few fishes appear somewhat earlier than this in the Ludlow formation, but nearly all the fish remains of the period occur in the very highest horizons regarded as Silurian, or in the deposits that form the transition to the Devonian period, where they are associated with eurypterids and land plants, as well as marine invertebrates. It would appear from the remains that fishes were rather abundant and varied in their development at certain stages. The relics, however, are fragmental and embrace teeth, dermal plates, spines, shagreen scales, etc. These fishes appear to have been the forerunners of the abundant fishes of the Old Red Sandstone (Devonian) into which the transition beds of Great Britain graduate, and as these Old Red Sandstone beds were probably land-water deposits, the association of the fish with the eurypterids and with land plants carries some further presumption that the peculiar crustacean fauna lived normally in land waters. It is not to be overlooked, however, that in the transition beds the fishes are also associated with marine fossils, and there is no question that, before the close of the Devonian period, certain fishes at least became truly marine. It is therefore entirely consistent with either view of the place of origin of fishes to regard these as marine forms, or as forms frequenting both salt and fresh water. It is to be noted further that not a few of the forms conveniently referred to here as fishes were probably ostracoderms which have certain arthropod characters and are not unlikely to be made a separate class, as will appear later.

CHAPTER VIII.

THE DEVONIAN PERIOD.

FORMATIONS AND PHYSICAL HISTORY.

THE division plane between the Silurian and Devonian systems is less clearly marked than that between the Silurian and the Ordovician. As already indicated, there is difference of opinion as to whether the Helderberg[1] formation belongs to the one system or to the other.

Whatever the final reference of the Helderberg formation, its relations to the immediately preceding and succeeding formations serve to show that the separation of the Devonian from the Silurian is less distinct than that of the Silurian from the Ordovician. Under either of these points of view, the sea again invaded the land early in the Devonian period, perhaps establishing some such relations as shown in Fig. 191. During the period, there were changes in the relations of land and water, some of which were of great importance in their effects on the life of the period. These will be noted later.

The subdivisions of the Devonian which have been commonly recognized in America (the Helderberg being included) are as follows, the several formations being numbered in chronological (and stratigraphical) order:

5. Chemung-Catskill:
    Chemung.
    Portage.
4. Hamilton:
    Hamilton.
    Marcellus.
3. Corniferous:
    Corniferous.
    Schoharie and Cauda Galli.
2. Oriskany.
1. Helderberg.

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[1] As originally classified, there was a *Lower* and an *Upper* Helderberg formation. The latter is now more commonly known as the *Onondagan* (Corniferous). In this volume the term Helderberg is applied to the former only. The adjective "lower" therefore becomes superfluous.

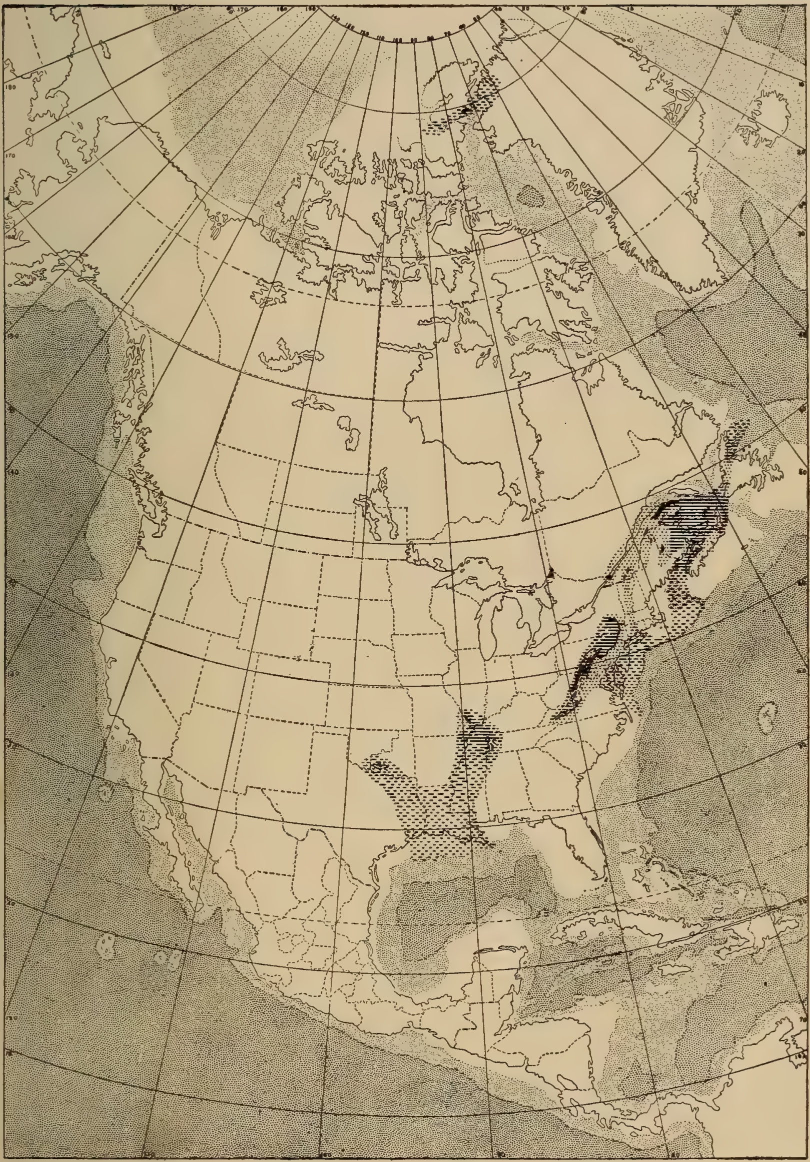

FIG. 191.—Map of North America, showing the outcrops of the Helderberg formation and the relations of land and water during the Helderberg epoch. The conventions are the same as in the earlier maps of the series.

The recently revised classification for New York[1] is as follows:

Devonic...	Neodevonic....	Chautauquan..	Chemung (including Catskill)
		Senecan.......	Portage beds Genesee shale Tully limestone
	Mesodevonic...	Erian.........	Hamilton shale Marcellus shale
		Ulsterian......	Onondaga (Corniferous) limestone Schoharie grit Esopus grit
	Paleodevonic...	Oriskanian.....	Oriskany beds
		Helderbergian..	Kingston beds Becraft limestone New Scotland beds Coeymans limestone

The new classification has an advantage over the old in that the same name is not used to indicate subdivisions of different importance, but the disadvantage of adding to the burden of nomenclature. The term Devonian will be retained instead of Devonic, and Lower, Middle, and Upper Devonian, as synonyms for Paleo-, Meso-, and Neo-Devonic, respectively. The subdivisions in the last two columns are to be regarded as appropriate for the New York region, and those of the second columns from the right may have wider applicability.

Recently revised classifications for Maryland[2] and the interior[3] are given below. In the latter, Helderberg is excluded.

Maryland.	Interior.
5. Hampshire = Catskill in part.	5. Chemung.
4. Jennings = Genesee and Portage.	4. Portage (including Genesee).
3. Romney = Erian.[4]	3. Hamilton.
2. Oriskany.	2. Onondaga (Corniferous).
1. Helderberg = Coeymans.	1. Oriskany.

THE LOWER DEVONIAN.

The Helderbergian series.—The known Helderbergian series is largely confined to the eastern part of North America. It is known (1) in Maine[5] and, beyond the United States, in Gaspé, New Brunswick, and Nova Scotia, and a remnant belonging to the same general province occurs near Montreal;[1] (2) in the Appalachian belt, and (3) in the lower Mississippi basin (see Fig. 191).

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[1] Clark and Schuchert, Science, Vol. X, 1899.

[2] O'Hara, Maryland Survey, Allegany County.

[3] Hayes and Ulrich, Columbia (Tenn.) folio, 1903.

[4] Prosser, Jour. of Geol., Vol. XII, p. 361.

[5] Williams, Bull. 165, U. S. Geol. Surv.

During the Helderbergian epoch, as before, the sea of the Appalachian trough seems to have had eastward, but not westward, connections. The fauna of the Appalachian Helderbergian beds is very similar to that of the region east of the lower St. Lawrence. From these relations it is inferred that the Helderbergian fauna of the eastern coast, like the Silurian fauna of the same region, found entrance to the Appalachian trough, and from relations which will not be detailed here, it is conjectured that the entrance was effected by an inlet near the present Chesapeake bay (Fig. 191). The fauna of the Helderbergian beds in the lower Mississippi basin is also of the Appalachian type, indicating geographic conditions which allowed of the migration of the Atlantic-coast faunas into this region.

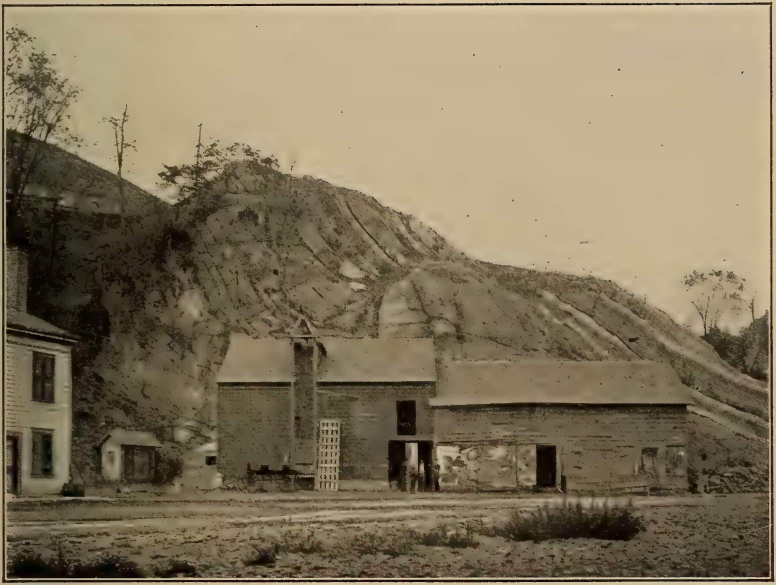

FIG. 192.—Helderberg limestone, Wilbur, New York. (Darton, U. S. Geol. Surv.)

The Helderberg formation is largely limestone, which suggests that subaërial erosion was not taking place at a rapid rate, and that the principal formation of the epoch, as far as our continental area is concerned, was extracted from the sea-water.

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[1] Whiteaves, Am. Geol., Vol 24, 1899, pp. 210–40. A review of the Devonian of Canada.

The Helderbergian series is 300 to 400 feet thick in eastern New York, and 350 to 600 feet in Pennsylvania. It thins to the west, being but a few feet thick in Ohio, and 100 feet or less in western Tennessee. In the vicinity of Gaspé, there is a continuous formation of limestone some 2000 feet thick, a part of which is of Helderbergian age.

The Oriskany.—The Oriskany formation is best known in the Appalachian region, but beds of the same age have a wide but undetermined distribution in the eastern part of the Mississippi basin, and in the St. Lawrence basin in the southern part of Ontario. Beds contemporaneous with the eastern Oriskany are more widespread than the eastern Helderberg formation. In the region where best known, the Oriskany is made up chiefly of coarse-grained sandstone. The vicinity of Cumberland, Md., may be regarded as the center of the Oriskany of the mountain belt. From this locality, it extends both northeast and southwest, but thins in both directions and loses its most distinctive faunal characteristics. To the westward, the faunal characteristics of the Appalachian belt are found as far as Cayuga in Ontario, indicating that the barrier between the Appalachian trough and the interior—a barrier which seems to have been effective since the Utica epoch—was removed during this epoch, allowing the life of the former region to migrate into the latter. In the southerly part of the Mississippi basin (western Tennessee) the Oriskany fauna also appears, though the formation in which it occurs (Camden chert) has no lithological likeness to the Oriskany of the east. In general, the beds of the interior, which are perhaps contemporaneous with the Oriskany of the Appalachian belt, are not sharply differentiated from the overlying beds, either lithologically or paleontologically.

As developed in the Appalachian belt, the Oriskany is a thin formation ranging from a score of feet in New York to several hundred feet in Maryland and Virginia.

In the northeast (Gaspé, New Brunswick, and Nova Scotia) the Helderberg formation has not been clearly differentiated from overlying parts of the Devonian system, but beds containing the Oriskany fauna have here an extensive development. In northern Maine (Moosehead Lake region) the Lower Devonian series (probably with other undifferentiated beds) is reported to have a thickness of several thousand feet.[1] From the testimony of fossils, both European and American, it is supposed that there was shallow-water connection between eastern North America and southern Europe, allowing marine life not at home in deep water to pass from the one continental region to the other.

THE MIDDLE DEVONIAN.

Local eastern formations.—In the east the Oriskany formation is succeeded by other clastic beds (Esopus, formerly called Cauda Galli, and Schoharie grits). Their equivalents have not been differentiated west of the Appalachian region. These formations are relatively thin, and are made up of sediments accumulated near shore.

The Onondaga.—They are succeeded by the Onondaga limestone, which is much more widely distributed, spreading from New York on the east to the Mississippi. Within this area, the Onondaga rests, now on Silurian[2] (Niagaran or later) beds, and now on Waterlime,[3] often with little evidence of unconformity, and with no intervening beds which carry an Oriskany fauna.

During the Onondagan epoch, the connection between the Atlantic and the interior by way of the Chesapeake region appears to have been closed (Fig. 193) but the descendants of the Oriskany fauna which had entered the Mississippi basin while the passage was open, are to be recognized in the fauna of the Onondaga limestone.

The lower beds of the Onondaga limestone may have been in process of deposition over the eastern interior while the Esopus beds were accumulating in the Appalachian belt. If this be the case the conditions for limestone accumulation were presently extended eastward

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[1] Williams and Gregory, Bull. 165, U. S. Geol. Surv., p. 22.

[2] Geol. Surv. of Iowa, Norton, Vol. IV, p. 127, and Calvin, Vol. VII, p. 54. See also Simonds, Arkansas Geol. Surv., Vol. IV, 1888; Hopkins, Vol. IV, 1890; Vol. II, 1891; Williams (H. S.), Vol. V, 1892. The presence of Middle Devonian strata in Arkansas is uncertain.

[3] Blatchley and Ashley, 22d Ann. Rept. Dept. of Geol., etc., of Indiana; and Sherzer, Geol. Surv. of Michigan, Vol. VII, p. 37; so also in Missouri, see Missouri Geol. Surv., Vol. XII, p. 67, and 22d Ann. Rept. U. S. Geol. Surv., Pt. II, p. 85; and Shepard, Missouri Geol. Surv., Vol. XII, pp. 67–82.

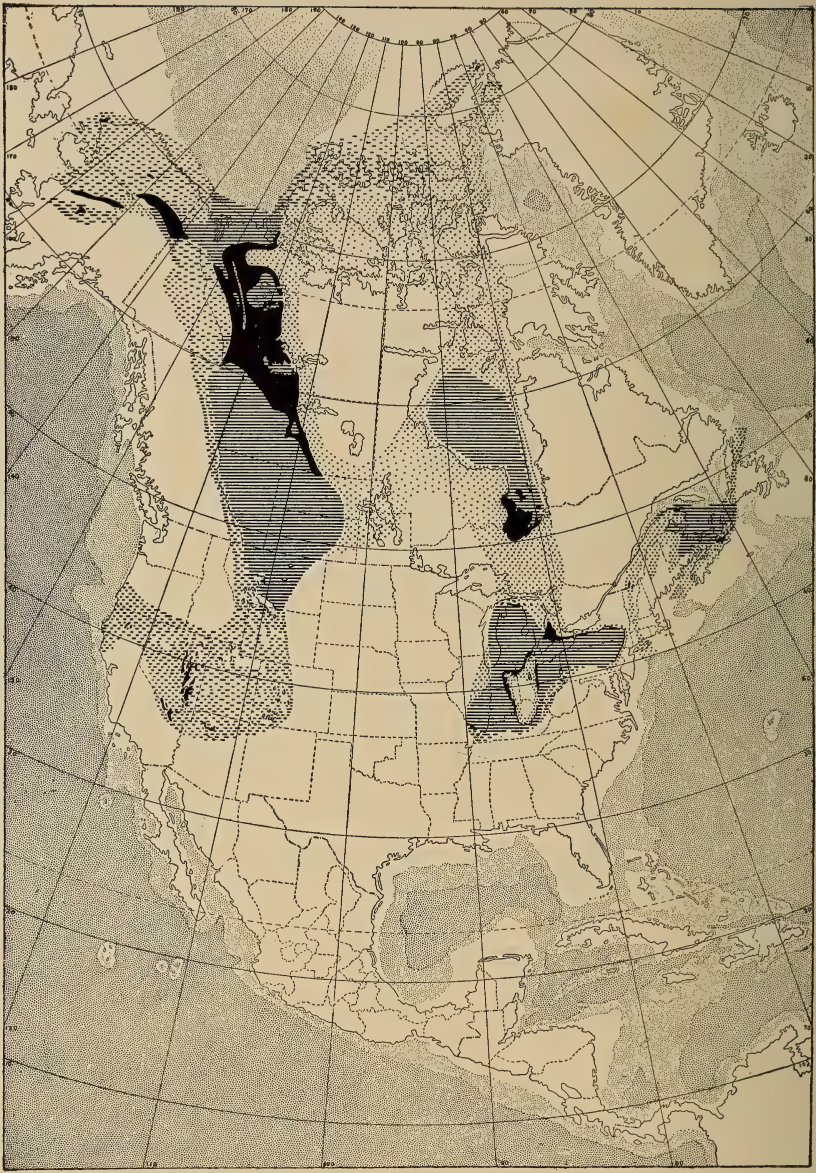

FIG. 193.—Map of North America, showing the outcrops of the Onondaga formation, and the relations of land and water during the Onondaga epoch. The Devonian at the northwest is not all Onondagan.

over the area where the clastic beds had been gathering, though locally clastic sedimentation may have continued through the epoch of the Onondaga limestone.[1] The general distribution of the formation and the general geography of the epoch are suggested by Fig. 193. A comparison of this map with Fig. 191 will give some idea of the changes which are thought to have taken place during this epoch.[2]

While the Onondaga limestone does not appear at the surface over extensive areas in the eastern part of the United States (Fig. 193), the area which it actually covers is much greater, since it is largely buried by younger formations. North of the United States, the formation occurs on the west side of James Bay (south of Hudson Bay). As will be indicated in connection with the account of the Devonian faunas, the new element in the Onondaga fauna of the interior may have come into the United States from the north. If so, the Onondaga of the Hudson Bay region was once connected with that of the interior of the United States.[3] The distribution of such formations as this and the Niagara (p. 377), convey some idea of the extent to which erosion has removed formations from regions which they once covered. The new types of life which appeared in the Onondaga, that is, the forms by which it is distinguished from earlier formations of the interior, seem to have reached Ontario and Michigan, perhaps from the north, at about the same time that the Oriskany types, entering the interior from the Atlantic, reached the same place. Such relations show the importance of paleontological studies in determining the geography of the past.

The constitution of the main body of the Onondaga formation shows that the water of the interior sea was relatively clear, and this in turn suggests that the surrounding lands were not sufficiently high to allow of rapid subaërial erosion. The limestone is often rich in corals, and the coral-reef structure is sometimes as perfectly shown as in the reef rocks of modern times. This is true, for example, at the rapids of the Ohio near Louisville.

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[1] The Newfoundland grit of New Jersey may be equivalent to the Onondaga limestone farther west: Weller, Report on the Paleozoic Paleontology of New Jersey, State Geol. Surv. of New Jersey, 1903.

[2] For an account of the Devonian in the Ohio basin, see Claypole, Am. Geol., Vol 32, 1903, pp. 15–41 and 79–105.

[3] Weller, Jour. of Geol., Vol. X, pp. 423–32.

The Onondaga limestone of the interior, often described under other names (Corniferous,[1] etc.) is usually not thick, rarely more than 100 or 200 feet, but it nevertheless represents a long interval of time, since limestone accumulates but slowly.

Onondaga limestone (or the equivalent of the Ulsterian series) occurs east of the Appalachian belt in northern New England and Canada where it has a distribution similar to that of the Helderberg.

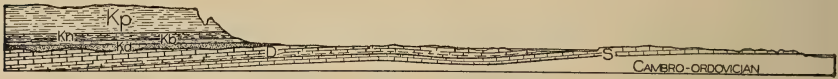

FIG. 194.—Section showing the relations of the Devonian system between Porcupine Mountain and the mouth of the Saskatchewan River. Length of section, about 125 miles. (Tyrrell, Geol. Surv. of Canada.)

At Gaspé, 800 feet of limestone, overlain by 1000 feet of sandstone, have been referred to the epoch. Though these beds may be the time-equivalent of the Onondaga of the interior, they do not contain the fauna characteristic of the formations of the interior, and their exact correlation is open to question.

The equivalents of the Onondaga beds, or of other subdivisions of the Middle Devonian of the east, have not been differentiated in the western part of the United States, nor in the great northwest territory of Canada, though the Devonian system is represented in both these great areas.

The map (Fig. 193) showing the outcrops of the Onondaga series represents an extensive outcrop in the northwestern part of the continent. This representation expresses the belief that the Devonian of this region includes the equivalent of the Onondagan. It probably includes also the later parts of the system. No Devonian formations are known to underlie the Great Plains of the United States.

The Hamilton or Erian series.—After a considerable period, during which there were relatively clear seas over the northeastern interior, conditions changed so as to give origin to deposits of mud where the Onondaga limestone had been accumulating. These mud beds and their equivalents, now consolidated, constitute the Marcellus and Hamilton formations of New York (see Fig. 195). West of Ohio and east of the Mississippi the equivalents of the two formations are commonly grouped together under the name Hamilton, or given local names (see Appendix, Vol. III). Shale is the most common rock at the east, but with it is associated not a little limestone, and in the west, limestone predominated. Southward, in Kentucky and Tennessee, the equivalent formations, where present,[1] consist largely of black shale and slate.

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[1] The name *Corniferous* was originally given to the Onondaga formation because of the local (New York) abundance of chert nodules which stand out (horn-like) when the limestone is weathered. These nodules are sometimes a foot or more in diameter, and often contain abundant shells of microscopic plants (diatoms, etc.), spicules of sponges, and teeth of annelids. Chert nodules are, however, hardly more characteristic of this formation than of many others, and the name is therefore an unfortunate one, and is gradually being set aside.

These changes in sedimentation appear to have been accompanied by changes in geography (compare Figs. 195 and 193). During the early part of the Marcellus epoch, the connection between the Atlantic and the interior by way of the Chesapeake may have been re-established.[2] At about the same time, too, considerable areas in the southern and in the northwestern parts of the Mississippi basin appear to have been submerged. In the Mississippi basin, the Hamilton formation probably overlaps its predecessor, resting on Silurian and perhaps even on Ordovician beds. The same relations hold in the southern Appalachians, where Devonian beds, probably the equivalents of the Marcellus and Hamilton, overlie Silurian and Ordovician unconformably. The submergence of the land in the south appears to have been sufficient to cause the sea to overspread areas which had been land since the close of the Ordovician (southern Appalachians and areas farther west) and perhaps to open up a connection between the interior sea and the Gulf of Mexico, allowing shallow-water species of animals to migrate into the Mississippi basin from the south, perhaps from South America (see Hamilton fauna, p. 460). The Cincinnati arch and the corresponding Nashville dome may have been land (islands or a peninsula, Fig. 195) throughout the Hamilton epoch, though this cannot be affirmed. If the Hamilton formation once overspread them, it has been removed by erosion. The map, Fig. 195, shows the general relations of the series, and at the same time suggests the geography of the epoch.

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[1] Hayes and Ulrich, Columbia (Tenn.) folio, U. S. Geol. Surv. This folio gives a late correlation table for the Ohio-Kentucky-Tennessee region.

[2] Ulrich and Schuchert, Bull 52 (Paleontology 6) New York State Museum, Report of the State Paleontologist, 1902, p. 654.

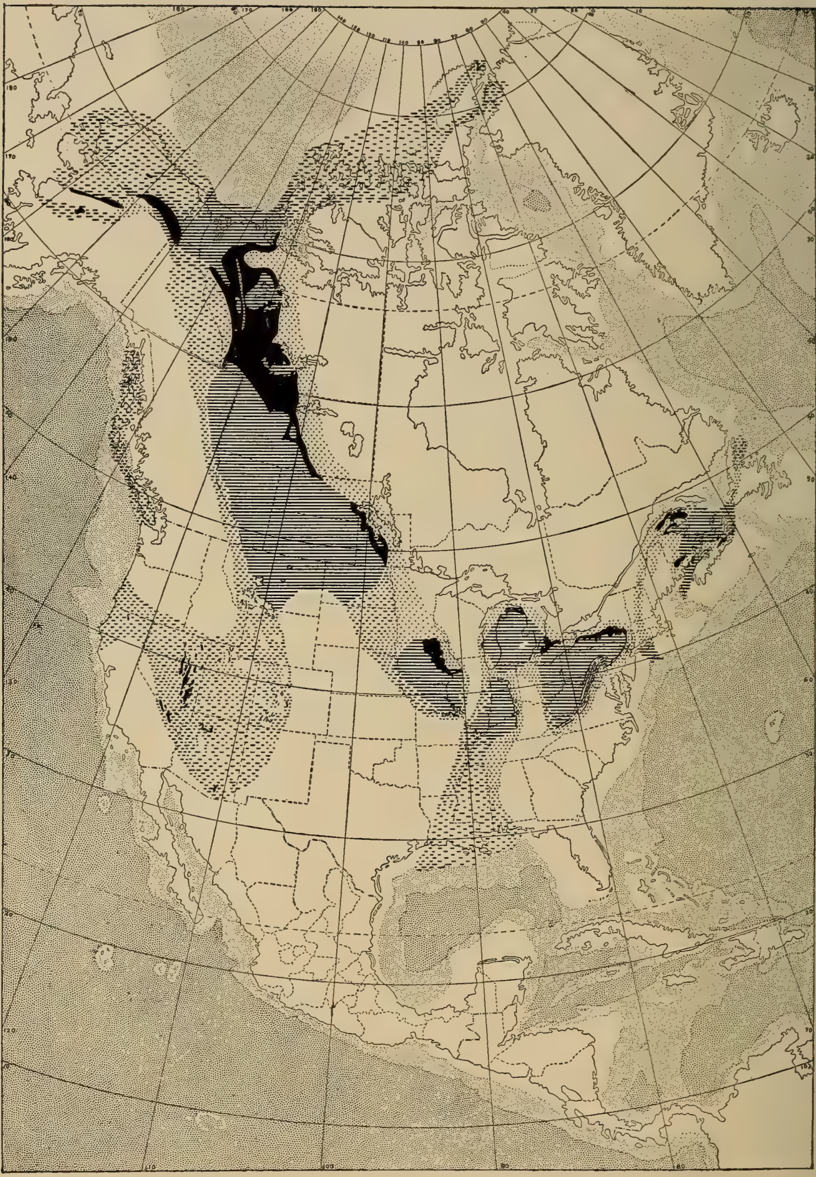

FIG. 195.—Map of North America showing the outcrops of the Hamilton formation and the relations of land and water during the Hamilton epoch. The black area at the north probably includes Lower and Upper Devonian as well as Middle. Compare Figs. 193 and 196. The conventions are the same as in earlier maps.

The conditions for the origin of the Hamilton shales would seem to be met if the surrounding lands (Appalachia and lands north of the interior sea), low and protected while the Onondaga limestone was making, were more elevated or less protected by vegetation, or subjected to more concentrated or spasmodic precipitation. Under the former conditions, the land formations would have been undergoing decay, but the products of the decay might not have been removed; under the latter, there would have been opportunity for the transportation of the products of decay. Even during the general period of shale formation, however, limestone (often shaly) was making in many places. This was especially true in the Mississippi basin, so that while the term "Hamilton shales" is in common use, "Hamilton shales and limestones" would describe more accurately the Erian series of this region. The Marcellus shale is locally more or less bituminous, indicating the presence of abundant plant life in the seas in which it was deposited.

In the east, the Hamilton (including Marcellus) formation is very thick, being 1500 to 5000 feet thick in Pennsylvania, where it is mainly of fragmental origin. Its thickness over the interior, where it contains more limestone, is but a fraction of this amount.

Middle Devonian in the northwest.—A considerable area of Devonian which has sometimes been called Hamilton is found in the basin of the Mackenzie river and southward to Manitoba.[1] The great arm of the sea in which the Devonian of this area accumulated appears to have extended as far south as northern Missouri (Fig. 195). Whether this arm of the sea antedated the Hamilton epoch is uncertain. Devonian beds, some of which may be the equivalent of the Hamilton, also outcrop along the main ridge of the Canadian Rockies.

The fossils of this northwestern Devonian do not correspond with those of the Hamilton formation of the east (Illinois to New York), and if the beds of the two regions were contemporaneous, as they may have been, they seem to have been deposited in waters which were not connected. The union was probably prevented by a narrow belt of land running south-southwest from Wisconsin to Missouri, somewhat as shown in Fig. 195. Till late in the Hamilton, this land seems to have constituted a barrier between the eastern interior sea, and a northwestern sea which stretched from Missouri on the southeast, through the Mackenzie basin, to the Arctic Ocean on the north. Toward the end of the Hamilton epoch, this barrier seems to have been removed sufficiently to allow the waters and the life on opposite sides to mingle freely. The removal may not have affected the whole of the barrier, but it seems to have been sufficient to accomplish the results indicated.

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[1] For review of the Devonian of Canada, see Whiteaves, Am. Geol., Vol. XXIV, 1899, pp. 210–40.

Belief in the barrier and in its removal is based primarily on paleontological evidence to be sketched later, but it may here be stated that up to the end of the Hamilton, the fauna to the west of the supposed barrier was unlike that to the east, while during the next succeeding epoch the fauna on the northwest seems to have invaded the eastern interior sea.[1]

The northeastern region.—Rocks (sandstone) of Middle Devonian age, presumably Hamilton, are known to occur in the eastern region (Gaspé), where some of them appear to be of fresh-water origin. The evidence of this origin is found in the abundant land-plant fossils. Some portions of these beds are probably the time-equivalents of the Hamilton of the interior, but their exact equivalency has not been established.

Geographic changes during the Middle Devonian.—The distribution of the Hamilton beds indicates several changes in the geography of the continent, as compared with that of early Devonian time. These were (1) a slight elevation (relative) to the east, interrupting for a time the connections between the sea of the Appalachian area and the Atlantic; (2) a subsidence to the southward in the interior, submerging areas which had long been land, and perhaps connecting the interior sea with more southerly waters; and toward the close of the epoch, (3) the removal of the barrier which separated the northwestern interior sea from the eastern. This last change may perhaps be looked upon as marking the closing stage of the Hamilton epoch.

THE UPPER DEVONIAN.

The Upper Devonian series has a distribution (Fig. 196) similar to that of the Middle Devonian, though it is perhaps less widespread

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[1] The Hamilton fish fauna of Wisconsin, Illinois, and Iowa is thought by Eastman to have been related to the Onondagan fish fauna of New York. Bull. Geol. Soc. Am., Vol. XIII, p. 537.

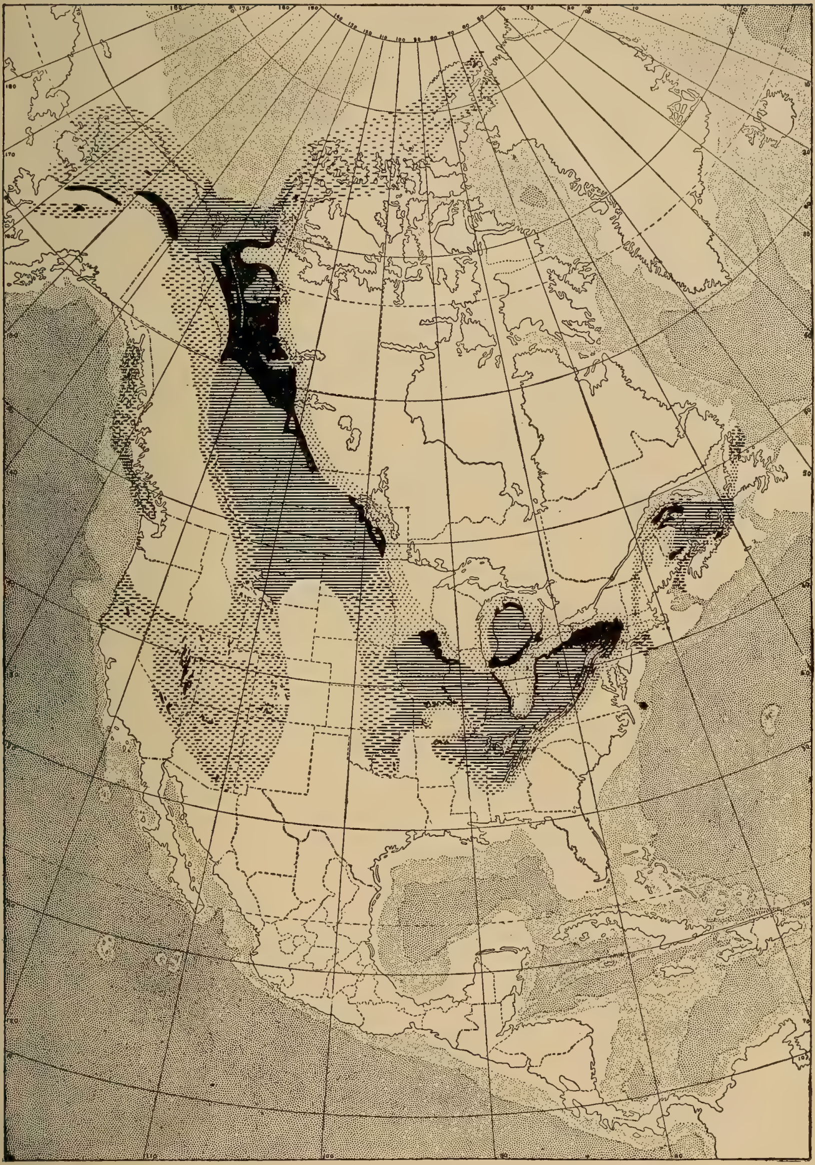

FIG. 196.—Map of North America, showing the outcrops of the Upper Devonian formations, and the relations of land and water in late Devonian time. The conventions are the same as in earlier maps (see p. 220). (See note under Fig. 195.)

to the south, on the whole, although in southwestern Missouri, Upper Devonian beds appear to be present where the older parts of the system are not known,[1] and the same relations appear to hold in northern Arkansas. In some parts of Iowa, the Upper Devonian is unconformable on the Middle (Fig. 197), but the separation of the Upper Devonian from the Middle is generally based on faunal rather than on stratigraphic grounds, the division being made where the distinctive Hamilton fauna gives place to another. The faunal changes which the upper Devonian records, seem to have resulted, in part at least, from the immigration of life from the northwestern sea of the previous epoch into the eastern interior. This immigration took place toward the close of the Hamilton epoch, and the invading species probably moved somewhat slowly from west to east, appearing earlier in Wisconsin than in New York. A connection between the Atlantic and the interior by the old route during the early part of the late Devonian (Portage, see p. 433) has been suggested to account for certain peculiarities of the Devonian faunas of this stage in the east.[2]

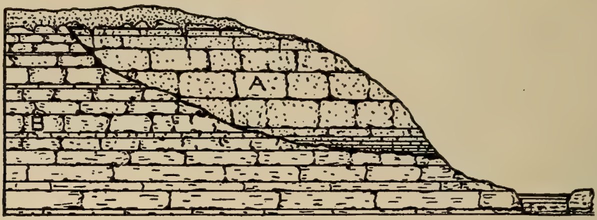

Fig. 197.—Hypothetical section showing the probable relations of the Upper (State Quarry) and Middle (Cedar Valley) Devonian, Penn Township, Johnson Co., Ia. (Calvin, Ia., Geol. Surv.)

The Tully, Genesee, and Portage formations, or Senecan series.—At the base of the Upper Devonian in New York, there is, locally, a thin bed of limestone (the *Tully*). At the horizon of this limestone, but where it has otherwise run out, there is a discontinuous layer of iron pyrites, which extends over a considerable part of western New York. The waters of this region were polluted by some iron compound (probably carbonate). The iron is believed to have been precipitated by sulphuretted hydrogen or ammonium sulphide derived from decaying vegetable or animal matter. This layer of pyrites is remarkable for its fauna of dwarfed species, 45 in number. The average size of the species is only about one fifteenth of the normal. Not only are the species dwarfed, but they represent species arrested in their development, appearing like the young of species of earlier Devonian types. The succeeding *Genesee shales* are black and bituminous, and range from a few feet (25 on Lake Erie) to a few hundred feet (150 in central New York, 300 in west central Pennsylvania) in thickness. The *Portage formation,* composed of shales and sandstones, is much thicker, being 1000 to 1400 feet in western New York. To the southward, its separation from the Chemung is less distinct than in New York. All these clastic beds bear evidence of shallow-water origin. Their stratigraphic relations are suggested by Fig. 186.

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[1] Shepard, Mo. Geol. Surv., Vol. 12, p. 65.

[2] Ulrich and Schuchert, op. cit., p. 656.

The Chemung and Catskill formations (Chautauquan series).—The Chemung formation of New York is very like the Portage, though more arenaceous. It is locally conglomeratic, and everywhere bears the marks of a shallow-water origin. Locally the conglomerate has been eroded into fantastic forms, giving rise to "Rock Cities," as near Panama in western New York. The formation ranges in thickness from 950 feet near Lake Erie, to 1500 feet in the vicinity of Cayuga Lake. Much greater thicknesses, 8000 feet maximum, are attained in Pennsylvania, but the formation thins rapidly westward. In northern Pennsylvania, the Cattaraugus formation overlies the Chemung, and a part of the Oswayo formation above the Chemung is also classed as Devonian.[1]

West of New York and Pennsylvania the Upper Devonian beds have few commonly recognized subdivisions, or none at all, and the eastern names are not in general use (see Appendix, Vol. III).

It may be here remarked that the Devonian was probably more extensively developed to the southwest than was formerly supposed. Devonian beds are said to occur at the summit of the Ozark uplift in Missouri,[2] though their present exposure in this region seems to be limited.

In the Catskill region, there is a series of red shales and sandstones which appear to be, in a general way, the time-equivalents of the Chemung. In some places the Catskill beds may represent less than the full Upper Devonian, and in others more. The Catskill formation is sufficiently different from the rest of the Upper Devonian to indicate that the sediments of which it is composed accumulated under conditions very different from those which obtained farther west. This formation is poor in fossils, and such as occur are partly, if not wholly, of fresh- and brackish-water forms. Hence it is inferred that the Catskill region was at least so far shut off from the ocean as not to afford the conditions necessary for marine life. The formation is notable for its redness, a feature which marks many other formations made in inclosed or partially inclosed seas, inland lakes, or basins.

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[1] Fuller, Gaines (Pa.) folio, U. S. Geol. Surv.

[2] Keyes, Bull. Geol. Soc. Am., Vol. XIII, pp. 268–292.

The Catskill formation has a thickness of 3000 feet in New York and twice that amount farther southwest in Pennsylvania. Local beds of sandstone (the Oneonta of central New York), seemingly like the Catskill in origin, occur outside the Catskill region, suggesting that similar conditions now and then existed farther west.

The thickness of the Upper Devonian in central and western New York approaches 4000 feet, and it is still thicker in Pennsylvania and Maryland,[1] locally reaching a thickness of 8000 or 9000 feet. In Ohio the same series (Black or Ohio shale[2]) has a maximum thickness of 2600 feet, but thins notably to the north and west, being at most only a few hundred, and often but a few score feet thick in Indiana,[3] Illinois, Iowa, southern Michigan, Kentucky, and Tennessee.[4] Various names are applied to the series and its subdivisions in various localities.

West of the Great Plains, the equivalents of the Chemung of the east have not been separated from other parts of the Devonian system. The Upper Devonian seems also to be represented in Maine and still farther northeast.[5]

The sections of the Devonian given in the Appendix, Vol. III, give some idea of the development of the system in various parts of the continent.[6]

[1] Prosser, Jour. of Geol., Vol. IX, pp. 415–42. This article is a concise summary of the Paleozoic systems of Maryland.

[2] Geol. Surv. of Ohio, 1873–93.

[3] Twenty-second Ann. Rept. Dept. of Geol. and Nat. Res. of Indiana, p. 17.

[4] Hayes and Ulrich, Columbia (Tenn.) and Campbell, London (Ky.) folios, U. S., Geol. Surv.

[5] Williams and Gregory, Bull. 165, U. S. Geol. Surv., p. 22.

[6] The Devonian of special regions east of the Great Plains is described in the text and shown on the maps of the following folios of the U. S. Geol. Surv.: *Ala-*

Devonian of the West.

The Devonian system, so far as known, is absent from the larger part of the Great Plains within the United States. This great expanse of territory was probably land during the Devonian period. No Devonian beds are found about the older formations in the Black Hills or in the vicinity of Hartville, Wyo., where the succession of formations has been studied in detail. The Helderberg is somewhat developed farther southwest in the Arbuckle Mountains of Indian Territory[1] (Woodford chert, see Appendix, Vol. III). The presence of Devonian beds in Texas is also uncertain, though Helderbergian beds at least probably occur in the southwestern part of that State.[2] The Devonian system has little development in the Rocky Mountains, but is somewhat widespread between the Rockies and the Sierras. It is represented in Arizona (Fig. 240),[3] Colorado,[4] Utah,[5] Nevada,[6] Wyoming (Fig. 247), and Montana,[7] and the Canadian Rockies.[8] Though its outcrops are not extensive, its actual area is obviously much greater. In some places, as about Globe, Arizona, the system is much faulted and affected by igneous

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bama, Stevenson, Gadsden; *Georgia*, Rome, Ringgold; *Kentucky*, Loudon, Richmond; *Kentucky–Virginia–Tennessee*, Estillville; *Pennsylvania*, Brownsville, Connellsville, Elkland–Tioga; *Pennsylvania–New York*, Gaines; *Tennessee*, Briceville, Chattanooga, Cleveland, Columbia, Kingston, Loudon, Maynardville, McMinnville, Morristown, Sewanee, and Standing Stone; *Tennessee–North Carolina*, Knoxville; *Virginia–Tennessee*, Bristol; *Virginia–West Virginia*, Monterey, Pocahontas, Staunton, Tazewell; *West Virginia–Virginia*, Franklin, Piedmont; *West Virginia*, Buckhannon.

Details concerning the system are also found in the geological reports of the several States where the system appears at the surface.

[1] Taff, Atoka (I. T.) folio, U. S. Geol. Surv.

[2] Hill, Physical Geography of the Texas Region, folio 3, topographic atlas, U. S. Geol. Surv., p. 4.

[3] Blake, Jour. Geol., Vol. IX, 1901, p. 68; and Am. Geol., Vol. XXVII, 1901 p. 164; Walcott, Am. Jour. Sci., Vol. XX, 1880, p. 221; and p. 436.

[4] Spencer, Am. Jour. Sci., Vol. IX, 1900, p. 125; Spurr, Mono. XXXI, U. S. Geol. Surv., pp. 9–30; Girty, Professional Paper, No. 16, U. S. Geol. Surv., pp. 156–162.

[5] King, Geol. Expl. of the 40th Parallel, Vol. I; see also Weller, Jour. Geol., Vol. X, pp. 423–32.

[6] Knight, Bull. 45, Wyo. Exp. Station; Yellowstone and Absaroka folios, U. S. Geol. Surv.; Spurr, Bull. 208, U. S. Geol. Surv.

[7] Little Belt, Fort Benton, Livingston, and Three Forks, Mont., folios, U. S. Geol. Surv.

[8] Dawson, Bull. Geol. Soc. Am., Vol. XII, p. 68, and Ann. Rept. Geol. Surv. of Canada, Vol. II, p. 19D.

rock;[1] in others it is bounded by unconformities, both below and above,[2] while in still others its limits are not sharply defined. In this western interior the system has not been generally subdivided, and where subdivisions have been made, they have not been correlated with those of the east. In the Great Basin region, Onondagan (Corniferous) types of fossils, and in overlying beds types corresponding to the Eurasian (rather than to the east American) faunas of the northwest, have been recognized. Hamilton types, with great vertical range also occur. The testimony of the fossils of the Basin region is to the effect that it was not connected either with the eastern interior sea or with South America in such a way as to allow of the free intermigration of marine life.

The system is 8000 feet (6000 feet of limestone and 2000 feet of shale) thick in the Eureka district of Nevada,[3] and 2400 feet (quartzite and limestone) in the Wasatch Mountains. In some parts of the west, as in the Yellowstone Park, the system is thin (160 feet[4]), and not divisible on physical grounds into distinct formations. In the western interior generally, limestone is the dominating formation.

Still farther west, on the Pacific side of the Paleozoic land area, Devonian is known in both northern[5] and southern[6] California, and may be represented in many places where the rocks are metamorphosed past identification. In the Klamath mountains, the Devonian (chiefly Middle) is much disturbed, and contains igneous rocks (tuffs and flows). The Devonian faunas of the coastal region, like those of the Great basin, are Eurasian in their affinities.

The Devonian system is also abundantly represented in widely separated parts of Alaska.[7]

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[1] Ransome, Professional Paper, No. 12, and Bisbee folio, U. S. Geol. Surv., pp. 39–46; also Reagan, Am. Geol., Vol. 32, p. 278.

[2] Am. Jour. Sci., Vol. XXVI, pp. 437–438, 1883.

[3] Geol. Expl. of the 40th Parallel, Vol. I; see also Weller, Jour. Geol., Vol. X, pp. 423–32.

[4] Weed, Yellowstone Nat Park folio, U. S. Geol. Surv.

[5] Diller, Am. Jour. Sci., Vol. 15, 1902, p. 344.

[6] Spurr, Bull. 208, U. S. Geol. Surv.

[7] Brooks, Bull. Geol. Soc. Am., Vol. XIII, pp. 256–61, and Professional Paper, No. 1, U. S. Geol. Surv., p. 211; Schrader, Bull. Geol. Soc. Am., Vol. XIII, p. 241: and Professional Paper, No. 20, U. S. Geol. Surv., pp. 62–67.

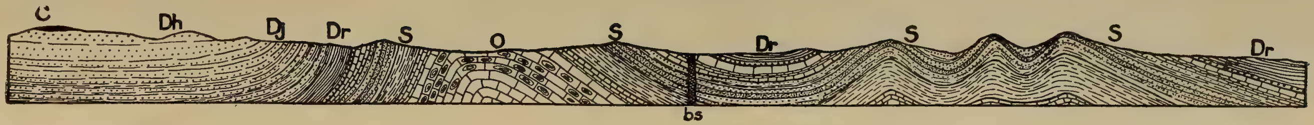

FIG. 198.—Section showing the relations of the Devonian in the Appalachians of Virginia and West Virginia. The section of the folio is modified to the extent of introducing a dike, *bs*. Dikes occur not far away, though not in this section. *O*=Ordovician; *S*=Silurian; *Dr* (Romney shale), *Dj* (Jennings formation), and *Dh* (Hampshire formation)=Devonian; *C*=Carboniferous. Length of section, about 14 miles. (Darton, Monterey folio, U. S. Geol. Surv.)

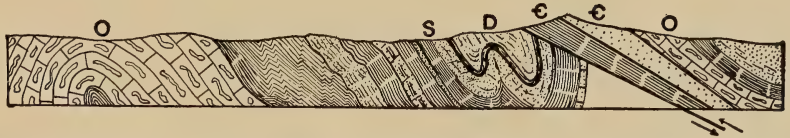

FIG. 199.—Section showing the Devonian in the region of Knoxville, Tenn. *Ꞓ*=Cambrian; *O*=Ordovician; *S*=Silurian, and *D*=Devonian. Length of section, about 5 miles. (Keith, U. S. Geol. Surv.)

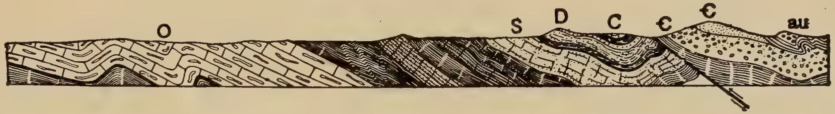

FIG. 200.—Section showing the relations of the Devonian and other Paleozoic systems in the vicinity of Loudon, Tenn. *Ꞓ*=Cambrian; *O*=Ordovician; *S*=Silurian; *D*=Devonian; ***au***=age unknown. Length of section, about 7 miles. (Keith, U. S. Geol. Surv.)

Areas Where the Devonian Comes to the Surface.

While the Devonian system is widely distributed it does not appear at the surface over large areas. Obviously in the beginning the Devonian formations were as wide-spread as the Devonian seas; but since most of the area of North America covered by the Devonian seas was also covered by the seas of later periods, the Devonian system was mostly buried. Subsequent withdrawals of the sea and warpings of the surface have allowed the overlying formations to be worn away, exposing the Devonian at many points, though in the aggregate the areas of exposed Devonian constitute but a small fraction of the area where the system is buried. It probably underlies much of the area in the eastern half of the United States where the Carboniferous rocks constitute the uppermost formations, and considerable areas in the west where younger formations conceal it. Strata of equivalent age must underlie much of the sea.

The absence of the Devonian strata in certain situations is hardly less significant than their presence at others. Thus it is to be noticed that between Iowa and Indiana, Devonian formations do not appear at the surface between the Silurian on the north and the Carboniferous on the south. The absence of Devonian beds here might indicate either that the deposits of the Carboniferous period extended farther north than those of the Devonian, concealing the latter, or that Devonian beds, once deposited north of the present border of the Carboniferous system, were worn away before the deposition of the latter. Of these alternatives, the former was, until recently, regarded the more probable; but a recent find near Chicago (at Elmhurst[1]) shows that the Devonian system, or some part of it, once covered a portion of the area where the Silurian beds now appear at the surface. Evidence of the former extension of a formation over an area where it does not now occur is usually found in the form of outliers (see Fig. 184 and p. 393); but in this case, the Devonian remnant does not constitute

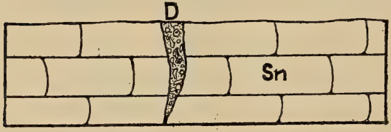

Fig. 201.—Figure illustrating the occurrence of remnants of Devonian material in fissures in Niagara limestone, near Elmhurst (Cook Co.), Illinois.

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[1] Weller, Jour. Geol., Vol. VII, pp. 483–8.

an outlier in the usual sense of that term. The remnant, quantitatively insignificant, occurs in a fissure in the Niagara limestone, as illustrated by Fig. 201. The limestone was apparently fissured before the Devonian above was deposited. Portions of the Devonian sediments fell into an open fissure, carrying with them distinctive fossils (fish teeth). In this protected position, the Devonian fossils escaped removal.

About much of the pre-Devonian area of southern Missouri, the Carboniferous and Silurian beds stand in the same surface relations as in northern Illinois, though Devonian probably appears between these systems in the southwestern part of the State. It is thought by some that most of the Ozark area was land during the Devonian period, and that the Carboniferous sea lapped up on it farther than the Devonian sea had done. The alternative view has been mentioned (p. 433). Similar relations are repeated in the Black Hills, in Texas, and at other points in the west, where the Devonian system outcrops more rarely than any other system of the Paleozoic except the Silurian.

As in the case of other systems, it is to be remembered that the line on the surface marking the junction of the Devonian with older formations in any particular region is not the line which marks the limit of the Devonian sea in that region. Erosion has shifted the outcrop of the system, and therefore the line of its junction with older formations. Erosion, too, has reduced the aggregate area of the Devonian as originally deposited.

Igneous rocks.—The general absence of igneous rocks in most parts of the well-known Devonian of the continent is to be noted; but in many parts of the west, and also in central New York,[1] the Devonian strata have been affected by dikes and intrusions of later times, and in Nova Scotia and New Brunswick there are igneous rocks which appear to be of Devonian age.[2]

CLOSE OF THE DEVONIAN.

The general period of quiet which had prevailed during the Devonian seems not to have come to an end at its close. Only in the eastern part of the continent, in Maine, Nova Scotia, New Brunswick, and

[1] Matson, Jour. of Geol., Vol. XIII., p. 264.

[2] Williams, Jour. of Geol., Vol. II, pp. 17–19.

the adjacent region to the north, do the Devonian strata appear to have been notably disturbed at the close of the period. Here the Devonian strata are overlain unconformably by the Carboniferous. Elsewhere the formations of the younger system rest on those of the older without stratigraphical break.

ECONOMIC PRODUCTS.

Gas and oil.—The Upper Devonian is the chief source of oil and gas in western Pennsylvania[1] and southwestern New York, and is one of the sources in West Virginia,[2] the oil being derived chiefly from porous beds. The Middle Devonian is the oil-producing series of Ontario (Enniskillen).

Within the regions of their occurrence, oil and gas are more likely to be found under low anticlines than in other positions, for the apparent reason that these furnish an inverted basin capable of holding these light substances against the superior pressure of subterranean waters which tend to force them to the surface. In all cases there must apparently be an impervious bed or combination of formations above, to prevent the escape of the oil and gas, and in this there is a certain similarity to the conditions requisite for artesian wells, but with the difference that the artesian wells receive their supplies from above and must be closed below, while the oil and gas wells receive their supplies from below and must be closed above. Both require a porous bed as a reservoir which, in the one case, ideally—but not always actually—forms a basin concave above, in the other, concave below. It is the general opinion of geologists that the oil and gas of the Devonian beds were derived from organic matter entrapped in the strata below, though distinguished chemists suggest an inorganic origin for many or most such products.[3]

The lower part of the Chattanooga shale of central Tennessee is the horizon of black phosphates, which are of considerable importance commercially.[4]

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[1] For report on the oils and gas of Pennsylvania, see Carll, Rept. I, 5 Penn. Geol. Surv., 1890. For statistics on the production of oil, gas, etc., see Mineral Resources of the United States, an annual publication of the U. S. Geol. Surv.

[2] White, West Virginia Geol. Surv., Vol. I, Oil and Gas, pp. 208 and 212. This volume is an important contribution to the literature of oil and gas.

[3] Orton, 8th Ann. Rept., U. S. Geol. Surv., Pt. II, and White, op. cit., p. 180 *et seq.*

[4] Hayes and Ulrich, Columbia (Tenn.) folio, U. S. Geol. Surv.

THE FOREIGN DEVONIAN.

The continent of Europe.—At the close of the Silurian there seem to have been more considerable geographic changes in Europe than in America, for the Devonian system is there more commonly unconformable on its base. This is especially true in the northern part of the continent. When these geographic changes took place, a number of inclosed or nearly inclosed basins containing inland water-bodies appear to have been developed in northwestern Europe. This conclusion is based on the character of the deposits made in this part of the continent, and especially on the fossils which they contain. It will be seen that in a general way the phenomena on opposite sides of the Atlantic corresponded, for considerable areas in America likewise suffered warping, and similar inland basins of water or other lodgement areas came into existence.

During the progress of the Devonian period, the European continent was progressively submerged, as is shown by the fact that the Middle and Upper Devonian formations are more wide spread than the Lower (Fig. 202). In this respect, also, the phenomena of Europe are in partial correspondence with those of America, though the Middle and Upper Devonian of Europe overlap the Lower, and rest on older formations more commonly than in America.

In keeping with the geographic changes which the distribution of the Devonian formations of Europe indicates, the Lower Devonian strata of western Europe are for the most part such as to imply a progressive advance of the sea on the land, but not without oscillations. The greater abundance of limestone in the Middle Devonian shows that the waters were clearer than in the earlier stage of the period, while the wider distribution of the Middle Devonian, as compared with the Lower, points to less extensive areas of land whence sediments could be derived. As in America, the Upper Devonian of western Europe is more largely of clastic material than the Middle, though it also contains some limestone.

Though the Devonian formations are widely distributed on the continent of Europe, they do not appear at the surface over any large area, except east of the Baltic in Russia. A lesser but still considerable area of Devonian appears in the basins of the Rhine and Moselle rivers in western Germany, and in the adjacent parts of Belgium and France. Aside from these larger areas, the Devonian is known in limited exposures at many points in the mountains of central and western Europe, in Germany, France, Austria, Hungary, Switzerland, Spain, Portugal, and Turkey. As a result of folding and faulting, the structure of the system is often very complex. Illustrations of the complex structure are shown in Figs. 203, 204, and 205.

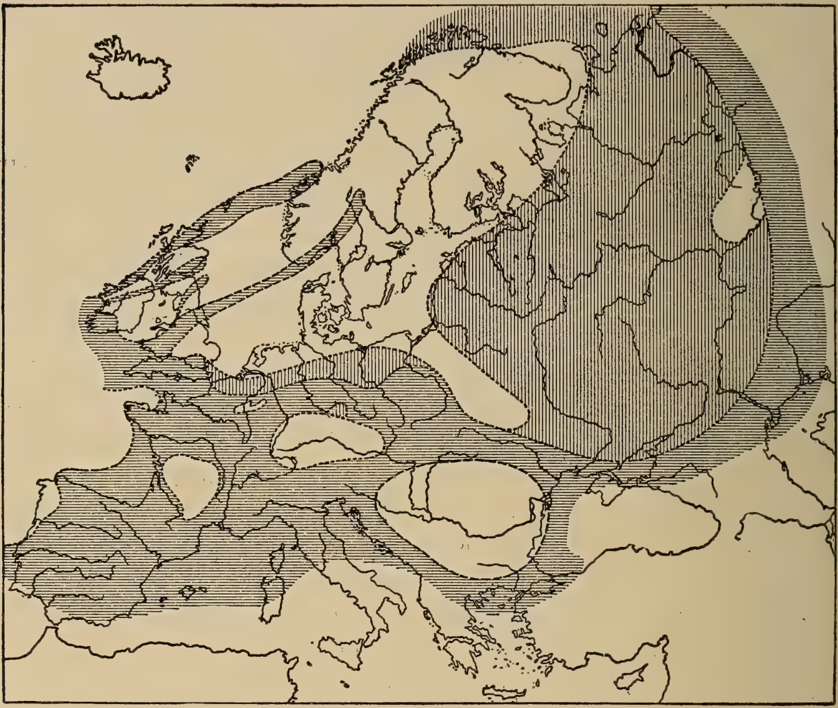

FIG. 202.—Sketch map of Europe during the Devonian. The horizontal lines represent the Lower Devonian; the vertical lines mark the additional areas where the Middle Devonian occurs. (After de Lapparent.)

The Lower Devonian is often conformable on the Silurian, but where the Lower Devonian is absent, and the Middle present, the latter rests unconformably on the Silurian, or on any other formation which may happen to serve as its base. This is its relation to the Cambrian in Belgium and northern France.

The areas where the Devonian beds outcrop are by no means an indication of their actual area, for they are to a large extent buried. The Devonian strata exposed in various parts of Russia are probably connected beneath younger beds. The Devonian system is also much more widespread in western Europe than its present outcrops indicate.

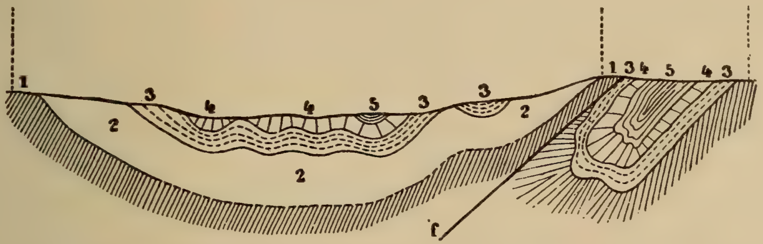

FIG. 203.—Section of the Devonian system of Dinant and Namur. 1 = Cambrian and Silurian; 2 = Lower Devonian; 3 = Upper Devonian; 4 = Carboniferous limestone; 5 = Coal Measures; *f*, fault. (Barrois.)

The British Isles.—In the British Isles the Devonian formation has two phases. The first is found in southwestern England in the area which gave the formation its name[1] (Devonshire). Here the system has a thickness of 10,000 or 12,000 feet, and, as shown by its fossils, is of marine origin. The structure of the Devonshire Devonian is so complicated that it is much less well calculated to furnish a key

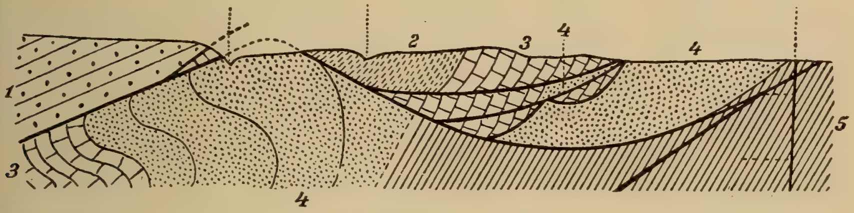

FIG. 204.—Section through the coal-field of Charleroi. 1 = Lower Devonian; 2 = Upper Devonian; 3 = Carboniferous limestone; 4 = barren, and 5 = coal-bearing Carboniferous formations. The heavy black lines indicate faults and overthrusts (Briart.)

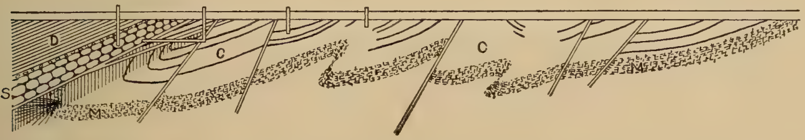

FIG. 205.—Section showing the coal-bearing formations, (*C*), beneath Devonian (*D*) and Silurian (*S*). *M* = Lower Carboniferous; *C* = Coal-bearing formations. (Pas-de-Calais; Barrois.)

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[1] The name Devonian was first used by Sedgwick and Murchison in 1839. Trans. Geol. Soc., 2d series, Vol. V, p. 688.

to the history of Devonian deposition than the corresponding strata of the Rhine basin. Igneous rocks are often associated with the sedimentary beds, and valuable ore-bearing veins sometimes result, as in Devon and Cornwall.

The second phase of the Devonian is the Old Red sandstone. This great series overlies the Silurian and underlies the Carboniferous. Its stratigraphical position is therefore clear, and it is thought to represent the Devonian. This phase of the Devonian is widely distributed in Wales, in west and north England, Scotland, in the Orkney and Shetland Islands, and in Ireland. It is possible that certain beds of Norway, doubtfully referred to the Devonian, are to be correlated with the Old Red sandstone phase of the Devonian in the British Isles. The same phase of the formation likewise re-appears in western Russia.

Concerning the history of the Old Red sandstone there has been much difference of opinion, but it is commonly held to have been deposited in a series of inclosed or nearly inclosed basins containing lakes or inland seas, the waters of which were fresh or brackish. It is further believed that crustal warping gave the sea occasional access to these basins. These conclusions are based on the nature of the formation, and on the testimony of its fossils. In general the strata are poor in fossils, and those which are present indicate that the waters in which the strata containing them were deposited were not the waters of the open ocean. Some of the fossils are fresh-water species, while others are land species. At some horizons, however, marine species occur. It is not improbable that some portions of this singular series are of subaërial, rather than subaqueous origin.

Against this interpretation several objections have been urged. In the first place, the presence of occasional marine fossils is thought by some to be against the inclosed-basin hypothesis.[1] The answer to this objection has already been suggested. A second objection is found in the wide extent of the formation, if it be referred to a single body of water. As partially meeting this objection, it is said to be probable that there was not a single inclosed sea or lake in which these beds were deposited, but rather many inclosed basins, and that no one was necessarily very extensive. Neumayr[2] also finds a difficulty in the way of the inclosed-basin hypothesis, in the great thickness of the Old Red sandstone, though admitting that it is no greater than that encountered in connection with other formations known to have been made in inclosed seas or lakes. The thickness of the beds is not very remarkable if they are interpretable as the results of inclined deposition.

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[1] Kayser and Lake, Text-book of Comparative Geology.

[2] Neumayr, Erdegeschichte, Vol. II, 1st ed.

The Old Red Sandstone formation, as its name implies, is mainly red and largely of sandstone. It, however, includes shales as well as sandstone, and the former, as well as the latter, are sometimes of a color other than that indicated by the name.

The Old Red sandstone of the British Isles is thought by Geikie[1] to have been deposited in several distinct basins. One of them extended westward from Scotland so as to include a part of Ireland, while another, that which includes the northern part of Scotland, the Orkney and Shetland Islands, perhaps extended eastward to southern Norway and finally still farther east to Russia.

It is to be noted that the Catskill formation of America has some features which suggest a comparison with the Old Red sandstone of Britain. Both are predominantly red, both are poor in fossils, and both seem to have been deposited in inclosed bodies of water. It is to be noted also that the one is in the eastern part of America and the other in the western part of Europe—regions where there are many other striking likenesses.

The Old Red sandstone formation of the British Isles consists of two great divisions, the upper of which in many regions lies unconformably on the lower. In such regions the lower division is conformable with the Silurian below, and the upper with the Carboniferous above. Since the Silurian below is not known to be the youngest Silurian, nor the Carboniferous above the oldest Carboniferous, it is not certain that the Old Red sandstone is the exact equivalent of the Devonian as elsewhere developed. It may include the upper part of the Silurian at its base, and the lower part of the Carboniferous at its top.

The lower division of the Old Red sandstone has a maximum thickness of something like 20,000 feet. It contains a large amount of volcanic rock. In this respect it corresponds with the Devonian of Germany. The aggregate thickness of the igneous rocks is, in Scotland, as much as 6000 feet, and the rocks are, in places at least, regularly interbedded with the sedimentary series. The eruptions seem to have been in part subaqueous, and in some cases so considerable as to build up the sea- or lake-bottom until it became land. As the result of the great erosion which has since taken place, the igneous rocks now form considerable ranges of hills (Pentland, Ochil, etc.). There are thousands of feet of sedimentary rocks without volcanic beds associated, both above and below the volcanic portions.

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[1] Trans. Roy. Soc. Edinburgh, Vol. XXVII, 1879. Also Text-book of Geology. 3d ed.

The upper division of the Old Red sandstone formation is not so thick as the lower. The unconformity between it and the lower division is a great one, and shows that changes of relations were taking place on a considerable scale. The bodies of water appear to have been shifted somewhat in position from time to time so that the formations made in one place at one time were exposed to prolonged erosion before they were again submerged and buried by younger strata.

In the upper division of the Old Red sandstone of Great Britain there are conglomerates of such a character as to have raised a question concerning the existence of glaciers in this region in Devonian times. The conglomerates contain bowlders of all sizes, up to eight feet in diameter. While the smaller stones are usually well worn, the larger ones are often distinctly subangular. All sorts of durable rock are represented. The large bowlders seem not to have come in from distant regions, but some of the smaller stones may have come from greater distances, since no local source for them is known. Furthermore, some of the bowlders are said to be *striated*, and it is believed by some geologists at least that the striæ are glacial. The matrix of the conglomerate is in keeping with the hypothesis that ice coöperated in its making. It has been suggested[1] that the Highlands of Scotland were then much higher than now, that they harbored glaciers, and that the bergs to which the glaciers gave origin made, or helped to make, the conglomerates here referred to. The conglomerate is to be seen in the Lammermuir Hills, and in the Silurian hills of Cumberland and Westmoreland, in northern England.

Fossils of the " Old Red " type have been found within the Arctic circle on Bear Island (lat. 70° 30′ N.), between the coasts of Norway and Spitzbergen, and both divisions of the Old Red have been recognized in Spitzbergen.[1]

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[1] Neumayr, Erdegeschichte, Vol. II, p. 133.

West central Europe.—The Devonian of Germany is remarkable for the proportion of igneous rock interbedded with the sedimentaries. The igneous rock is principally diabase and diabase tuff, but other varieties are also found. These rocks occur in many separate beds, showing that there were many periods of igneous activity separated by intervals of quiet. Igneous rocks occur in the Devonian in some other parts of western Europe.

In much of central-western Europe the Devonian strata have been metamorphosed, and their structure is often complex. In not a few places, especially where the sedimentary rocks have been invaded by igneous rocks, mineral veins have been developed whence large quantities of iron, tin, copper, and other metals have been obtained.[2] The Devonian of Germany also contains a little coal, showing that the conditions for its formation were locally present.

Russia.—The Devonian of Russia is made up of beds of arenaceous and calcareous rocks, the former containing fossils related to those of the Old Red sandstone, the latter containing fossils of a marine fauna. The Lower Devonian appears to be wanting in much of Russia, and the middle and upper parts of the system are generally unconformable on subjacent formations. Except in the Ural region, where Lower Devonian is present, the Devonian strata of Russia are not notably disturbed.

Comparison with America.—On the whole, the course of geological history seems to have been less pacific in Europe than in America. The great local unconformities within the Devonian system find no parallel, so far as now known, in America, and the extreme development of igneous rock in western Europe is not duplicated in America.

In Europe as in America, there do not seem to have been notable changes at the close of the Devonian. There seem to have been some changes of level in Russia, Bohemia, and Great Britain, so that succeeding strata rest with some measure of unconformity on the Devonian; but over much of the continent the Carboniferous strata succeed the Devonian conformably. In this again the European phenomena correspond with those of America.

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[1] Geikie, Text-book of Geology, 4th ed., Vol. II., pp. 1012 and 1013.

[2] Ibid., p. 995.

Other continents.—The Devonian system has a wide distribution in Siberia and China, where its faunal relations are with northern Europe. It is known in Asia Minor, Persia, and northwestern India (Himalayas and eastern Tibet). It perhaps has wide distribution in North Africa (Atlas mountains, Sahara), in South Africa (Cape Colony), and in the Falkland islands. Glacial beds of Devonian age have been reported recently from South Africa.[1] The fauna of the South African Devonian has South American affinities. The system has considerable development in South America, and carries an indigenous fauna akin to the Hamilton fauna of North America. So far as identified in this continent, the Devonian beds are referable to the upper part of the Lower Devonian, and to the lower part of the Middle.[2] The system attains a thickness of 10,000 feet in New South Wales,[3] Australia, and has been recognized in Victoria. With the Middle Devonian sedimentary formations of Victoria, felsitic lavas and tuffs are associated. Devonian(?) rocks are the oldest known formations of the North Island, New Zealand, and attain great thickness—7000 to 10,000 feet[3]—in the South Island. Kayser[4] recognizes two great Devonian provinces, viz., the *Eurasian*, including a large part of north and central Asia, and probably extending to Manitoba, and the *American*, including much of the United States, South America, and South Africa.

DEVONIAN LIFE.

I. THE MARINE FAUNAS.

General faunal evolutions. — It may be recalled that the early marine faunas of the Cambrian period were interpreted as regional or provincial in type, but were found to merge into a more general type toward the close of the period. The Ordovician fauna was regarded as really little more than a continuation and expansion of the Cambrian fauna and as singularly general at its climax. After a repressional interval, the Silurian fauna seems to have developed into a similar cosmopolitan type, followed by a restrictive evolution. It is now to be noted that the Devonian period, in America at least, brought again an evolution of provincial faunas, but on an unusually large and declared scale, and of an advancing phase, verging toward cosmopolitanism.

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[1] Schwarz, Jour. Geol., Vol. XIV, p. 683, 1906.

[2] Kayser, Geologische Formationskunde.

[3] Geikie, op. cit., p. 999.

[4] Idem, Zweite Auflage, p. 154. Other and minor faunal provinces are defined by Lebenden, Mem. du Comité geologica, XVII, No. 2, pp. i–x, and Barrois.

The ancestors of the Devonian faunas are found remotely in the cosmopolitan fauna of the Silurian period, and more immediately in the restrictional faunas of the closing Silurian. The early Devonian faunas are to be regarded as the expansional phases of these restrictional faunas. Fortunately the physical conditions during the Devonian evolution are better known than those of previous stages when provincial faunas were undergoing development, and hence reveal in a specially instructive way the conditions under which such faunas develop. Even here, however, the data recorded are far from complete, and only a part of them have been critically studied as yet, so that whatever conclusions are now entertained must be held subject to correction. By way of precaution, it is to be recalled that the faunas here under discussion are those of the relatively shallow water that lay about the continental border, or on the bosom of the continent itself, in the form of intruding gulfs and interior seas. The land life, to be considered later, had its own independent phases of development, while the faunas of the abysmal depths of the ocean and of the surface of the mid-ocean are almost wholly unknown.

Special faunas evolved.—With the partial withdrawal of the sea from the North American continent, as sketched in the previous chapter, the mid-Silurian fauna underwent restrictive evolution and differentiation in the embayments on the continental border. For want of free communication between these embayments, their faunas developed distinctive aspects. When the sea re-advanced upon the land in the early Devonian, it was by tongues or invading gulfs from different points on the continental border, these being in part extensions of the border embayments. Each of these gulfs seems to have had its own rather distinctive fauna, inherited from the embayments of the coast border.

Five such faunas seem to have invaded the continent of North America during the Early and Middle Devonian, partly in succession and partly simultaneously, viz.: (1) the Helderberg, (2) the Oriskany, (3) the Onondaga (Corniferous), (4) the southern Hamilton, and (5) the northwestern Hamilton. These reached the interior in succession in the order named, and the faunas are described mainly as they are found to have been developed at the stage when they succeeded one another in the interior, but all must have had earlier stages during which they were evolving and advancing upon the continent along their particular lines of invasion. As each in succession came into contact, through the coalescence of the advancing gulfs or seas, with the fauna that had previously invaded the region, there was a commingling and conflict of the various assemblages, resulting in the elimination of some species and the adjustment of others to one another. The result was a fusion of the forms surviving from the two faunas, and the development of a new composite fauna. In this fusion, one or the other of the faunas was usually dominant and gave the chief characteristics to the new fauna.

The originating tracts of the invading faunas.—The places of origin of these faunas cannot be determined at present with certainty, but the following are the suggestions of present evidence, and may serve as working hypotheses until fuller data shall establish permanent interpretations. Of the Helderberg fauna, the more local elements probably originated in the great embayment at the mouth of the St. Lawrence and on the border of the adjacent continental shelf. The less local element seems to have been derived from the coast border of the (then) North Atlantic, which seems to have connected the American continent with southern Europe, but not directly with northern Europe. The Hercynian fauna which characterizes this stage of the Devonian in southern Europe has much in common with the Helderberg fauna of America, while both were markedly different from the early Devonian fauna of northern Europe and northern America, although a fauna of Helderbergian aspect has been detected at one locality in the far northern islands.[1]

Giving precedence here to the local American phase, it is to be noted that in the St. Lawrence embayment the strata show a gradual passage from the Silurian fauna up into the Helderberg fauna. It will be recalled that the St. Lawrence embayment was a harbor of refuge for the Ordovician life when it was forced to retire and undergo transition into the Silurian type. History seems to have acquired the habit of repeating itself thus early. The Helderberg fauna seems to have advanced from the coast-border region of the Middle States into the Appalachian valley trough, and to have spread westward and northward as far as the advancing waters permitted. If the interior waters did not extend southwesterly to the Helderberg areas of Tennessee, Illinois, and the Indian Territory, the access to these regions was probably gained through embayments from the more southerly coast. The fauna seems never to have occupied the great interior Mississippian region generally.

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[1] Meek, Am. Jour. Sci., ser. 2, Vol. XL, p. 31.

The Oriskany fauna, which followed the Helderbergian in this region, appears to have entered the interior region along the same tracts as the Helderbergian, but to have spread farther westward, even as far as western Ontario, while the Helderbergian fauna only reached central New York. In its dominant phase, it was a sand-loving fauna and crept along the arenaceous tract adjoining the old Appalachian land and the northern shore of the interior sea. In other areas where the deposit was calcareous, the fauna assumed a modified phase.[1] The general identity of its lines of invasion with those followed by the Helderbergian fauna, and the occurrence of species of Oriskany aspect in the St. Lawrence embayment, offer some suggestion as to its place of origin. A very significant fact also is the occurrence of some very peculiar Oriskany-like species in South America. This hints at the possibility that the fauna either developed along the Atlantic coast in a horizon now entirely buried, and certain of the species spread down the coast and reached South America, or else, originating at the south, certain species spread up the coast until they found access to the interior through the inlets mentioned. Some part of the fauna perhaps spread on to Europe and to Africa, or else was derived thence and spread westward, since allied species occur in those regions. It is also quite possible that some notable part of the fauna developed in the St. Lawrence embayment at a stage later than the evolution of the Helderberg fauna, when the deposits became sandy, as they did, and that thence there was migration more or less simultaneously southward along the coast to South America, westward into the interior, and northward and eastward to Europe and Africa. The more typical species of the Oriskany, however, do not seem to have been directly derived from Helderberg species, but to have been evolved in some distinct area. The typical Oriskany fauna, on invading the regions already occupied by the Helderberg fauna, mingled with it and hence a Helderberg element was present.

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[1] Clarke, J. M., Mem. N. Y. State Mus., No. 3, Vol. 3.

As to the originating tract of the Onondaga fauna, still less is known, but in its maximum extension it occupied the whole of the great interior Mississippian sea, which had not been the case with either of the preceding faunas. A very characteristic development of this fauna is found along the north side of the interior basin in the vicinity of the straits of Mackinac, and the suggestion hence arises that the fauna invaded the interior sea in this region from the north, along a tract from which the deposits have since been removed (see map, Fig. 193) Less than three hundred miles to the north, in the James Bay basin, the fauna has much the same facies as that nearest it on the south. While there is no positive evidence of a former connection across the intervening tract, there seems to be no inherent improbability in such connection.[1] Besides these geographic relations there are general considerations, as will be seen later, for believing that this fauna had a northern origin, and had communication with northern Europe.

Almost the only light on the originating tract of the eastern Hamilton fauna is found in the fact that a very similar fauna lived in South America (Bolivia, Brazil, and the Falkland Islands) at about the same time, and that some quite peculiar forms are common to the two.[2] A southern origin seems therefore the most probable, and this is in reasonable harmony with the distribution of the strata containing it. It is hence inferred that this fauna entered from the south along the Mississippi tract, which may not improbably have been open at this time, as there is direct evidence of land subsidence in that direction.

Concerning the northwestern Hamilton fauna,[3] there is evidence that it gradually crept down from the north, probably along the tract that is now the Mackenzie valley, and that for a time it was not in communication with the area occupied by the southern Hamilton, but that at length it passed over the intervening barrier that seems to have stretched from the old lands of Wisconsin to the similar old lands of Missouri. Thence it invaded the eastern interior sea and overran the territory already occupied by the southern Hamilton fauna [1] (see map, Fig. 196).

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[1] Weller, Jour. of Geol., Vol. X, p. 423.

[2] Williams, Bull. U. S. Geol. Surv., No. 210, p. 79.

[3] Williams, idem.

Bearing in mind that these suggestions relative to the origin and invasion of the America interior by these great provincial faunas are subject to correction by new data, they may be taken provisionally to represent the leading faunal movements of the early and middle Devonian in the interior and eastern portions of the continent. These successive invasions may be likened to the barbarian invasions of southern Europe in medieval times. As in the latter case, the precise origin of the invading hosts is subject to doubt and can only be approximately inferred, but the later stages of the invasions and their consequences are more or less clearly discernible, and constitute the most declared features of this romantic period.

In the Great Basin there seems to have been a very slow and conservative evolution as though the area was largely isolated, or at least protected from such faunal inundations as those that overwhelmed the eastern region. This region and that of the Pacific coast will be treated later.

The Helderberg Fauna.

Assuming that the Helderbergian fauna was derived from the Silurian fauna, it should have been differentiated from it in a less degree than were the Oriskany, Onondaga, and Hamilton faunas at the time of their respective invasions, for less time had passed previous to its appearance in the interior. This is conspicuously true. The fauna bears a strong Silurian facies, and, on account of this, has often been classed as Silurian. It had, however, undergone so much change from the parent fauna that, with but two exceptions, so far as now known, the species were all new. These two exceptions were the cosmopolitan species *Leptœna rhomboidalis* and *Atrypa reticularis*, species remarkable for their wide range and long life. Considered as species, they were the Methuselahs of the Paleozoic times.

In that portion of the originating tract that lies in the St. Lawrence embayment, there are over 2000 feet of shales and shaly limestones, forming a continuous series, in the lower part of which the fossils are predominantly Silurian and in the upper part predominantly Devonian, while in the central thousand feet the two types are commingled or are replaced by intermediate forms. From this intermediate or transitional assemblage the Helderberg fauna seems to have taken its origin in part at least, and to have emigrated westward as the re-advance of the sea permitted.

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[1] Weller, Journ. of Geol., Vol. VI, p. 306.

The marked development of the mollusks.—As the physical conditions in the originating tract gave a muddy, partially calcareous bottom, the fauna developed in lines suited to such a habitat and, as like conditions prevailed in the interior to which it emigrated, it retained its original character as a silt-conditioned fauna. As a consequence, mollusks and molluscoids greatly preponderated, and trilobites were fairly developed, while corals and crinoids, lovers of clear water, were relatively few and unimportant. The gastropods came into unusual and quite peculiar prominence. The capulids, a rather inferior or degenerate type, seem to have found singularly congenial conditions, for they appeared in great variety of form. Two characteristic forms of this group are illustrated in Fig. 206, *a* and *b*. The group continued to play an important part in the faunas that occupied the interior in succession during the following stages of the Devonian period, whether because, having come in with the Helderberg immigrants, they held their own notwithstanding the subsequent invasions by other faunas, or because new forms came in with each of these invading faunas, does not now clearly appear, though the former seems the more probable. Especial interest attaches to this group because it constitutes one of the characteristic features of the Hercynian fauna in Europe, a fauna which has been the subject of much difference of opinion but which is, with little doubt, the essential equivalent of the American Helderberg. A number of gastropods other than the capulids were present.

The bivalves also blossomed out notably in large-winged forms, the aviculids (Fig. 206, *c*). This was in sharp contrast to the Niagara fauna, which showed but few of these forms. Like the capulids, they continued to be numerous through the succeeding Devonian faunas.

Quite in contrast with the foregoing, the cephalopods had a very meager development. From being one of the dominant types in the Silurian, they fell to an insignificant rank. They were to rise again, however, in a new form.

The superior numbers of the molluscoids.—The inevitable brachiopods far surpassed all other classes in numbers. They were even more

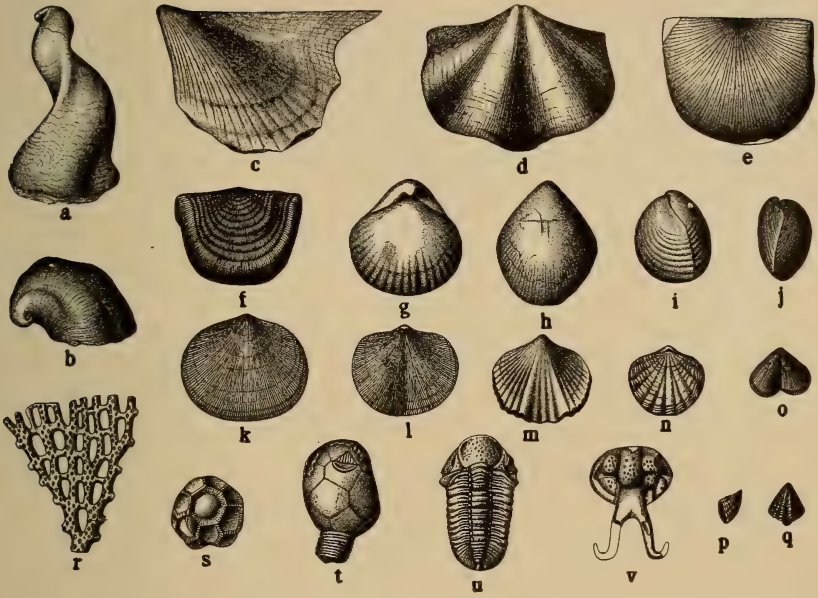

Fig. 206.—The Helderbergian Fauna. *Gastropoda: a, Platyceras spirale* Hall; *b, Platyceras gibbosum* Hall, two forms of the capulid shells which abound at some localities in the Helderbergian and which have their great development in the Devonian faunas. *Pelecypoda: c, Actinopteria textiles* (Hall), one of the winged pelecypod shells which have so great an expansion in the Devonian faunas. *Brachiopoda: d, Spirifer macropleurus* (Con.), a species which is more closely related to the Silurian than to the Devonian members of the genus; *e, Strophonella punctulifera* (Con.). The members of this genus are more characteristically Silurian than Devonian although it persists to the Middle Devonian; *f, Leptæna rhomboidalis* Wilck., a species which ranges from the Ordovician to the Mississippian (see Fig. 163); *g, Gypidula galeata* (Dal.), one of the most characteristic species of the Lower Helderbergian or Coeymans fauna; *h, Rensselæria æquiradiata* (Con.), a representative of a genus peculiarly characteristic of the Lower Devonian; *i, Uncinulus mutabilis* (Hall), a representative of a genus of rhynchonelloid shells which has its greatest development in the Helderbergian faunas; *j, Schizophoria multistriata* (Hall), and *k, Rhipidomella oblata* (Hall), shells representing two types of orthids having their greatest development in the Devonian faunas; *l, Dalmanella subcarinata* (Hall), another orthid of a group more strongly represented in earlier faunas; *m, Eatonia medialis* (Van.), a representative of a genus most characteristic of the Lower Devonian faunas; *n, Atrypina imbricata* (Hall), a lingering Silurian type; *o, Bilobites varicus* (Con.), a type of orthid characteristic of the Silurian and Helderbergian; *p–q, Cyrtina dalmani* Hall, a member of a genus feebly represented in the Silurian but which has a great development in the Devonian faunas. *Bryozoa: r, Polypora lilæa* (Hall), one of the fenestelloid bryozoans, a group having a slight representation in earlier faunas, but attaining great prominence later. *Corals: s, Michelinia lenticularis* Hall, the earliest member of a genus of corals which becomes abundant in later Devonian faunas. *Cystoidea: t, Lepocrinites gebhardii* Con., one of the last representatives of the cystids, a group of echinoderms having their greatest expansion in Ordovician and Silurian times. *Trilobita: u, Phacops logani* Hall, the genus Phacops, though present in the Silurian, has its great development in the Devonian; *v, Dicranurus hamatus* (Con.), an acidaspid whose closest relative occurs in Barrande's étage *G*, in Bohemia. (Weller.)

numerous in genera and species than in the Silurian period, but did not develop such tangible peculiarities as the gastropods and pelecypods. Illustrations of leading forms will be found in Fig. 206, *d* to *q*. There were many members of the *Orthis* family (Fig. 206, *j*, *k*, and *l*) which gave a somewhat Silurian facies to the fauna, but a study of the details of these forms shows the initiation of the Devonian type of development. The members of the *Strophomena* family (Fig. 206, *e*, *f*) were also very abundant and much diversified, a foreshadowing of their much greater development in the succeeding Onondaga and Hamilton epochs. The spirifers (Fig. 206, *d*) had come to be a striking feature of the assemblage. They had made a very notable advance upon their relative place in the Silurian fauna. Several of the Helderberg spirifers were clearly successors of Silurian species and represent consecutive evolution, but a larger number were not so much lingering representatives of known earlier forms as initial forms of new types which were to be more fully developed in the succeeding Devonian faunas. The loop-bearing brachiopods appear at this time in the genus *Rensselœria* (Fig. 206, *h*) which reached its maximum development in the next epoch.

The bryozoans were fairly developed and foreshadowed coming types, rather than represented past types (Fig. 206, *r*).

The aberrant tendency of the trilobites. — The trilobites distinguished the epoch by their notable tendency to sport, a tendency which reached its climax later. They took on strange and distinctive forms, one of which is illustrated in Fig. 206, *v*. The peculiar shapes of the head parts and their remarkable ornamentation seem inexplicable unless they had an esthetic function, which would presuppose a high mental development. But, whether explicable or not, the development of the ornamented and erratic forms represents a stage in the evolution of the class quite worthy of note, not only as characteristic of the Devonian evolution, but as a precursor of the approaching disappearance of the whole group. It will be seen later that as the trilobites neared the end of their career their forms became aberrant.

The scantiness of the crinoids and corals.—The crinoids had fallen from their former high estate in the Silurian to an insignificant place, not fatally and finally, but temporarily, on account, we may suppose, of the rather turbid waters which the shales and shaly constituents of the limestones indicate. The cystids (Fig. 206, *t*) suffered less relatively, but they were not abundant. The other echinoderms were still less important.

The corals, doubtless for like reasons, were not generally abundant, though *Favosites* was well represented, as were also a few other forms. The genus *Michelinia* (Fig. 206, *s*), which became abundant in the Onondaga and Hamilton epochs, makes its first appearance here.

Minor forms.—There were hydrozoans, among which *Stromatopora* became so common as to form, almost alone, beds three or four feet thick; a few graptolites, which were about to become extinct; some sponges, and doubtless not a few other forms that have escaped fossilization.

The notable absence of fishes.—It is to be especially noted that fish remains are almost or quite absent from the Helderberg deposits, although they had appeared in the epoch just preceding and reappeared in great abundance and in remarkable forms in the Onondagan epoch that soon followed. However their absence is to be explained—and it seems to be nearly inexplicable—it serves to strengthen the belief that the Onondaga fauna originated in a tract well isolated from the originating tract of the Helderberg fauna.

The Oriskany Fauna.

The key to the interpretation of the typical Oriskany fauna appears to lie in the fact that it was a sand-loving assemblage of species and that its habitat was the sand-flats that skirted the ancient shore belt. There was a minor phase of the fauna found in calcareous deposits. The fauna was bound by many close ties to the Helderberg, especially that phase of it which is present in the more calcareous beds, but it contained also distinct features implying in part a separate origin. However originated, it was so constituted as to fit the conditions of shallow water and sandy bottoms, while the Helderberg fauna was adapted to calcareous and muddy bottoms, and perhaps to somewhat greater depths. The Oriskany fauna, as we know it, was also later than the Helderberg, which means that in so far as it was not derived from the Helderberg, it had been developing longer since the two diverged from a common stock, and should therefore be farther removed from the common Silurian parentage. Whatever the source of the Oriskany fauna, it appears to have been developed outside the interior basin and to have followed the Helderberg fauna into the interior as a distinct invasion.

Preponderance of large brachiopods.—More than half of all the known species of the Oriskany fauna are brachiopods.[1] Their most obvious feature was their great size. The *Pentamerus oblongus* (Fig. 187, *o*) of the Silurian period and a few other previous forms had been large, but at no time had there been a fauna made up of species from different genera and even different families which attained such ample dimensions as those of the Oriskany. *Spirifer arenosus* (Fig. 207, *e*), *Rensselœria ovoides* (Fig. 207, *a*), *Stropheodonta magnifica* (Fig. 207, *f*), *Hipparionyx proximus* (Fig. 207, *b*), and *Camarotœchia barrandi* (Fig. 207, *c*), all reaching lengths or breadths of two and one-half to four inches, made up an aldermanic group that seems all the more notable for its sandy habitat, though sandiness at the bottom of the sea does not imply sterility in the same sense as sandiness on the land. There were small brachiopods associated with these giants, but they were

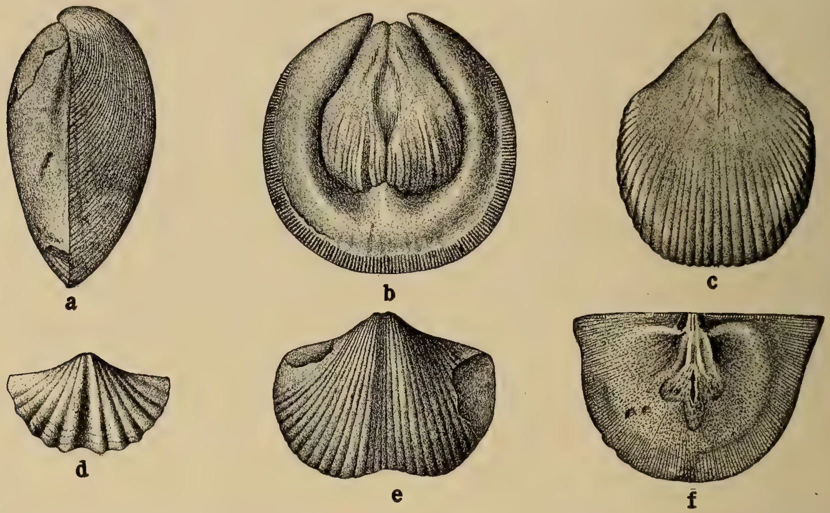

FIG. 207.—THE ORISKANY FAUNA. *Brachiopoda: a, Rensselœria ovoides* (Eaton); a representative of a genus restricted to the Helderbergian and Oriskany (see Fig. 206, (*h*); *b, Hipparionyx proximus* Van., one of the most characteristic fossils of the arenaceous Oriskany beds; *c, Camarotœchia barrandei* (Hall), one of the large rhynchonelloid shells of the Oriskany; *d, Spirifer murchisoni* Castel, and *e, Spirifer arenosus* (Con.), two of the most characteristic Oriskany species, the first occurring throughout the fauna, the second mainly in the fauna of the arenaceous beds; *f, Stropheodonta magnifica* Hall; a species which sometimes grew to be four or five inches across. The genus has its great expansion in the Devonian. (Weller.)

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[1] Schuchert, Rept. N. Y. State Geologist for 1888, p. 51.

less impressive as a factor of the fauna. The brachiopods of the Oriskany were largely of the same genera as those of the Helderberg, but the species were new. Some of the genera, as *Eatonia* and *Rensselæria,* were confined to these two faunas; others had a wider range. Of the latter, many were represented later in the Onondaga, and some in the Hamilton faunas.

It is important to note that in South America there were several species which bore a strong Oriskany facies, and in some cases there was complete specific identity, as in the notable form *Anoplotheca flabellites.*

Mollusks abundant and large.—While the mollusks were much less amply represented than the molluscoids, they showed some striking characters which help to further characterize the fauna. The gastropods were the most abundant of the mollusks, and the capulids were their leading form, as in the Helderberg epoch. Not less than 60% of all the known Oriskany gastropods were capulids. Some of them were exceptionally large and plump, reaching lengths of four inches, and mouth-expansions of two and a half inches. The Helderberg capulids had been without spines, but the spine-bearing species *Platyceras nodosus* appeared in the Oriskany fauna, although it became more conspicuous in the later Onondagan.

The pelecypods were not very abundant, but, like the brachiopods and gastropods, they were phenomenally large and coarse, some of them being five inches across. These unusual sizes, affecting three distinct types, imply that the cause lay in conditions congenial to the types and not in the types themselves, except as they were well constituted to respond to the conditions. The pteropods were represented by the *Conularia*—and even that was large—and by large tentaculites; while the former powerful cephalopods were reduced to a single species, so far as the known record shows.

Scantiness of trilobites, corals, crinoids, and fish.—The trilobites were not abundant and were chiefly species that had a larger development in the Onondaga. They were perhaps even Onondagan forms that became mingled with the late Oriskany forms after the two faunas came in contact, as explained later. In the calcareous phase of the Oriskany, however, there were several trilobites more or less closely allied to Helderberg forms. Corals, crinoids, and cystoids were rare, as might be expected from the nature of the formation; so also were the bryozoans and most of the minor types. Fishes were also wanting, though the reason is not evident. In a word, the Oriskany fauna was essentially an assemblage of well-fed mollusks and molluscoids with a scant sprinkling of other forms.

There was a fauna in South America that contained Oriskany-like forms. The Helderberg type is not known to have preceded it there. The wide-ranging habitat along the coast of the Atlantic, which this seems to imply, was probably the main home of the fauna, and its incursion into the interior was probably but an episode in its history which happens to have been better recorded than the main chapter.

The Onondaga Fauna.

The presence of true marine fish.—The Onondaga fauna is most strikingly distinguished from the preceding ones by the appearance of a host of fishes of highly developed and divergent types. There is no reasonable ground to doubt that these were true marine fishes, whatever may have been true of the fishes of the late Silurian and of the transition beds discussed in the last chapter, and of the Old Red Sandstone fishes to be discussed later in this chapter under the head of fresh-water life. The Onondaga fishes were intimately associated with marine invertebrates of the most typical kind, and in the most typical way, and there were none of those peculiar associations with gigantic crustaceans, land plants, and a strange pauperitic group of invertebrates, which seemed to place the previous fish faunas in a special category. Confirmatory of the true marine character of these fishes is the fact that they had successors in the succeeding marine deposits, and left a consistent record from that time to the present. Instead of occasional and sporadic appearances in special localities, such as characterize the record from the Ordovician period up to this time (and which perhaps merely imply occasional incursions or inwashes from land-waters), there was now a continuous occupancy of the seas, for from this time on fishes ranged widely through the epicontinental waters of America and of Europe, and doubtless of the seas generally. Their numbers in the Onondaga waters were very great, though the list of known genera and species is small. A notable feature of the record consists of " bone beds," thin layers made up almost exclusively of the plates, teeth, spines, and dermal ossicles of fishes whose numbers must have mounted into the millions. One of these occurs near Columbus. Ohio, and another near North Vernon, Indiana. Newberry[1] describes the relics as fragmentary and worn, and suggests that they may be the undigested residue of innumerable feasts of the larger fishes upon their weaker kin. It is possible that there were restricted tracts or passageways of the shallow sea through which the inferior fish habitually passed for reasons connected with the depths, currents, tides, food-distribution, or other sea conditions, and that in so doing they were the victims of persistent attacks by their superiors, and thus the bottom became strewn with the débris of the slaughter. At the present time, sudden changes of temperature due to the shifting of currents destroy great numbers of fish simultaneously and probably give rise to great fish deposits. Were it not for the fragmentary condition of the relics of the ancient bone beds this would seem to offer the most plausible explanation.

The fragmentary nature of the remains makes a satisfactory identification and classification difficult and not a little revision of those first made has been found necessary; still further changes will doubtless yet be required. What is said about kinds and classes must therefore be taken with some reserve. It is clear, however, that an extinct order of fishes, arthrodirans (joint-necked), formed a signal feature of the fauna; that sharks of several orders also constituted a large element; that certain of the ancient ganoids (crossopterygians), were present, and doubtless other forms. The arthrodirans, whose necks were so joined to their bodies as to give their heads vertical motion, a rare feature in fishes, were quite remarkable forms, and perhaps held the leading place. Among them were the *Macropetalichthys*, whose skull is illustrated in Fig. 208, *a*, and *Dinichthys* (terrible fish) which rose to monster sizes a little later (Fig. 209, p. 463) and then rapidly declined. The sharks embraced not only forms armed with cutting and piercing teeth, but also forms provided with pavement teeth for crushing shell-fish. The *Teleostomi* were of the ancient type (ganoids, chiefly crossopterygians) which were usually characterized by cartilaginous skeletons and bony scales, in contrast to modern teleosts, which are characterized by bony skeletons and membranous scales. In general the fishes of the time seemed to have been more fully clothed with spines and defensive armor than modern fishes. Compared with existing species they were doubtless heavy and clumsy in movement, and sluggish and brutal in habit.

From the degree of adaptation to sea conditions already attained,

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[1] Paleozoic fishes of North America, Mono. XVI, U. S. Geol. Surv., 1889, p. 30.

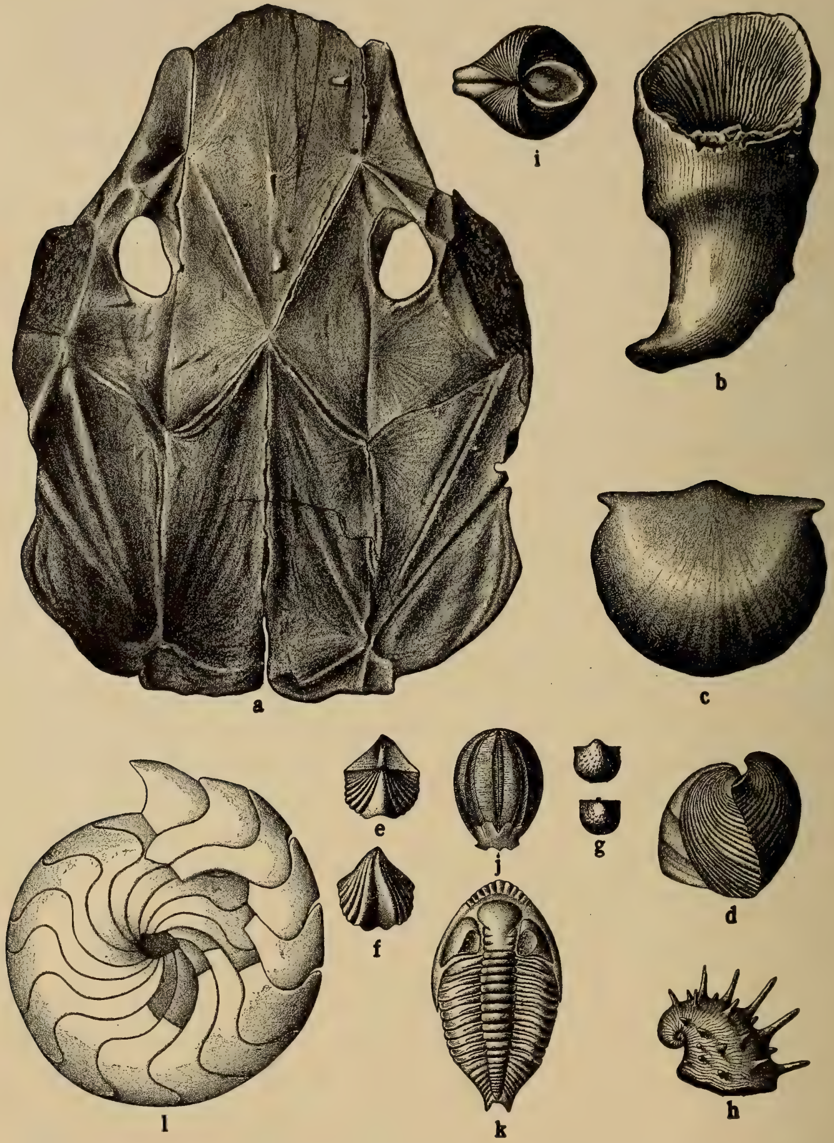

Fig. 208.—The Onondagan (Corniferous) Fauna. *Vertebrata: a, Macropetalichthys sullivanti* Newb. The figure represents the head of one of the most characteristic Onondaga fishes. *Coral: b, Zaphrentis ponderosa* Hall. The figure represents a medium-sized, simple, horn-coral. *Brachiopoda: c, Stropheodonta concava* Hall, and *d, Spirifer acuminatus* (Con.), two of the most characteristic Onondaga brachiopods; *e, f, Cyrtina hamiltonensis* Hall, two views of a species having a wide geographic distribution, and a long geologic range in the Middle and Upper Devonian faunas; *g, Productella spinulicosta* Hall, one of the earliest representatives of a genus which became wonderfully abundant in the Upper Devonian, and gave rise to the typical *Productus* of the Mississippian and Carboniferous faunas. *Gastropoda: h, Platycerus*

[*Continued on bottom of p. 463.*]

it is probable that they had been living for some time in the sea in the originating tract of the Onondaga fauna somewhere in the northern region. It is not impossible that fish were inhabitants of the northern seas from the late Silurian on, but not of the more southerly seas previous to the time of this invasion, since their relics are absent from the preceding Helderberg and Oriskany formations. Several of the genera of the arthrodirans and sharks have been found in the deposits of Germany (*Dinichthys*, *Macropetalichthys*, *Machæracanthus*), implying that they lived in the interior sea of Europe as well as that of America.

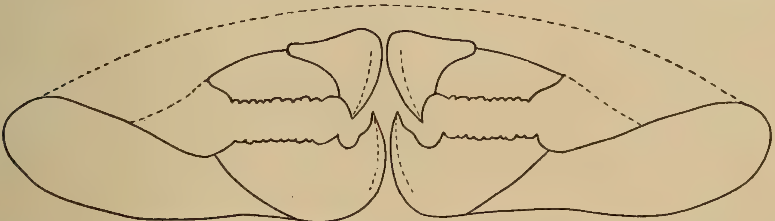

FIG. 209.—Diagrammatic front view of the dentition of *Dinichthys herzeri*, Huron shales, Delaware, O. (After Newberry.)

Others (*Acanthaspis* and *Onychodus*) have been recognized in the Lower Devonian deposits of Spitzbergen, directly supporting the suggestion of a northerly distribution.

The profusion of corals.—Another significant feature of the Onondaga fauna was the extreme abundance of corals. From the rapids of the Ohio at Louisville there have been collected more than two hundred species deemed worthy of illustration. Other localities add greatly to the total list. These embrace both the simple cup form (Fig. 208, *b*) and the compound type. Some of the former reached extraordinary sizes, as in the case of *Zaphrentis gigantea*, individuals of which sometimes attained a length of eighteen inches and a diameter of three inches. The general range in size was wide, small and large being intermingled, though the large preponderated. The salient expression of the epoch, however, lay not so much in the advance of

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dumosum Con., a capulid shell with large, hollow spines. *Pelecypoda: i*, *Conocardium trigonale* Hall, a dorsal view of a common Onondaga pelecypod. The genus occurs in the Silurian and also in the Mississippian. *Echinodermata: j*, *Nucleocrinus verneuili* (Troost), a blastoid which occurs in great numbers in one layer of the Onondaga limestone in the Ohio valley. *Trilobita: k*, *Odontocephalus ægeria* (Hall), one of the dalmanites, showing the development of ornamentation on the border of the head and tail. *Cephalopoda: l*, *Tornoceras mithrax* (Hall). This is the first goniatite to appear in the faunas of America. The goniatites are distinguished from earlier representatives of the cephalopods by their lobed sutures. (Weller.)

the corals as organisms as in their great luxuriance and relative prominence. The reef-building habit which had appeared in the Niagara epoch reached a fuller expression at this time, the reef at the rapids of the Ohio being the most famous example. This luxuriance of the corals implies clear seas abundantly enriched with floating organic matter. This seems in turn to imply that the higher lands and steeper slopes which had perhaps given a notable inwash of sand and silt during the two previous epochs had given place to lower land, doubtless densely clothed with vegetation—the result, very likely, of an approach to base-leveling.

The unequal development of the crinoids.—That the profusion of corals, however, did not find its sole explanation in clear genial waters rich in food may be inferred from the relative poverty of the same sea in crinoids which affect like conditions. In the Niagara epoch the crinoids and the corals flourished together in luxuriance. In the Onondaga, the corals were phenomenally prolific, while the crinoids were, with local exceptions, rather scant. This is the more remarkable in view of the subsequent, as well as previous, abundance of the crinoids. That the physical conditions were not uncongenial seems to be shown by the fact that the individuals present were usually large and bore no signs of repressive environment, but rather the opposite. The repressive conditions are possibly to be found in some untoward feature of the transition from the Niagara epoch, which gave precedence to their competitors, the corals, an advantage which they held throughout the epoch to the measurable exclusion of the crinoids, or else in some undeterminable organic agency.

Cystoids have not been found. They were far down their declining curve to be sure, but were not yet extinct, for they appear in the following period. The blastoids were represented (Fig. 208, *j*), but the other echinoderms, like the cystoids, have not been found, and these other branches were yet in their ascending stages. There was doubtless something in the conditions originating the Onondaga fauna that was adverse to the whole order, while favorable to the corals.

The changes in the brachiopods.—The ubiquitous brachiopods, as usual, formed a large constituent of the fauna, both individual and specific. Many were large and gave evidence of congenial conditions. The spirifers (Fig. 208, *d*) and the stropheodonts (Fig. 208, *c*) were the most characteristic types. The majority of the spirifers, however, had a retrogressive look, in that the fold and sinus were generally free from plications, as in the earlier types. Some, however, were plicated on the fold and sinus, as were many of the later spirifers and *S. arenosus* (Fig. 207, *e*) of the Oriskany period before. The plications on the sides of the shell of one of the Onondaga spirifers (*S. acuminatus*, Fig. 208, *d*) were sometimes bifurcated, a character that was rare among Devonian brachiopods, but which became common in the Carboniferous period. The loop-bearing shells, which first appeared in the Helderberg, attained an increased importance. The productids, which had been represented in the Niagara epoch by *Chonetes*, were now represented in addition by *Productella* (Fig. 208, *g*), a deep concavo-convex shell with spines scattered over the surface, foreshadowing more definitely than the *Chonetes* the great development of the *Productus* family in the Carboniferous period. The punctate shell, which became an important characteristic in the later Paleozoic faunas, had its first notable development in the Onondaga, where it appears in both the spire-bearing shell, *Cyrtina* (Fig. 208, *e* and *f*), and in the loop-bearing shell, *Cryptonella*. Meristoid shells, which were particularly abundant in the Helderberg fauna, were few in the Onondaga, as were also the orthids, while the pentamerids had dwindled to minor importance.

The notable development of the cephalopods.—The mollusks contributed several very notable features to the fauna. The cephalopods in particular presented characters in striking contrast to those they bore in the Helderberg and Oriskany faunas. It will be recalled that the cephalopods were very meagerly represented in those faunas. In the Onondaga, however, they were present in great abundance in the old types, and in addition, they presented an important new one, the lobate-sutured goniatites (Fig. 208, *l*). It will be remembered that in the primitive types of the cephalopods the septa of the shells were plain, or symmetrically curved, and that the line of juncture with the outer shell was a simple curve. In the goniatites, the septa were abruptly bent and the suture-line lobed, as illustrated in Fig. 208, *l*. This was the first notable step in the flexation of the septa and of their sutures, a character which was to attain remarkable complication in the Mesozoic era. Had this new and divergent type appeared alone after the dearth of cephalopods in the Helderberg and Oriskany faunas, it might have been attributed to the repressive conditions which that dearth seems to imply, but the old forms accompanied it in notable abundance, as already remarked. Seventy species of cephalopods are described from this fauna in New York alone. They were particularly abundant in the Schoharie grit (p. 422), which occupied the same district and had the same essential characters as the Oriskany sandstone, which had been so barren of cephalopods. They were also abundant in the calcareous tracts farther west, thus exhibiting their relative independence of bottom conditions, as might be expected of free-moving, predaceous animals. While the orthoceratites did not reach the gigantic dimensions of their Ordovician predecessors, individually they attained fair sizes, three inches in diameter being not uncommon. The club-shaped *Gomphoceras* appeared in many large species, and the curved *Cyrtoceras* and *Gyroceras* were abundant, while the closely coiled *Nautilus* was present but not abundant. The ornamentation of the exterior was a notable feature, but quite inferior to the elaborate ornamentation which it foreshadowed. This prolific retention of old forms, combined with the introduction of a new type, points apparently to some distinctive set of conditions which distinguished the history of the Onondaga fauna, either in its originating tract, or in its expansional stage, or in both.

The persistence of the previous types of the gastropods and pelecypods.—On the other hand, it is to be noted that the gastropods were present in abundance and largely in the same peculiar facies that they had assumed in the Helderberg and Oriskany faunas. As there, the capulids were numerous, though perhaps less abundant. The acquisition of spines, which was initiated in the Oriskany fauna, became a pronounced feature in this (Fig. 208, *h*), and perhaps signified that there was occasion for defense, an occasion which either the fishes or the cephalopods could doubtless have supplied. There were many other forms of gastropods, including *Euomphalus*, coiled in a plane, and *Murchisonia*, coiled in a very high spire. These, with the cap-shaped capulids, filled out a full complement of gastropod types. There was a notable similarity of the gastropods to those of the Helderberg and Oriskany faunas, which seems to imply derivation from them, in contrast with the peculiarities of the cephalopods which seem to imply an origin from some other fauna.

The pelecypods were also abundant and often resembled those of the Helderberg and Oriskany from which many of them were descended. The large oblique-winged aviculids were again conspicuous, and *Conocardium* (Fig. 208, *i*), distinguished by the flattening of one end and the protrusion of the other, reappeared, having been absent from the Helderberg and Oriskany, after being represented by several species in the Silurian.

The revival of the trilobites.—Trilobites were present in more than half a hundred species, a notable increase over the known species of the same region in the preceding epoch. The presence of a remarkable number of highly ornamented species was a conspicuous feature. Spines, nodes, and granulations freely diversified their somewhat erratic forms. The dalmanites led in this decorative movement, though the species here represented (Fig. 208, *k*) is a modest form. As far back as the Niagara, this genus had shown its ornamental tendencies, but it only reached its maximum display in the Onondaga epoch. Its chief rivals in these lines were the acidaspids and lichads. Other crustaceans were but sparingly represented, the barnacles alone having been found thus far.

Other forms.—Of other types, there were annelids, sponges, hydrozoans, bryozoans, and probably protozoans, all of which played inconspicuous though, in the economy of the whole, doubtless not unimportant parts.

The foregoing sketch has been based essentially upon the aspects presented by the Onondaga fauna as found in the eastern interior basin. In the James Bay region its facies is not well known. Corals were a conspicuous element and the identification of the fauna has been based chiefly on them. Fishes were also present there, a fact to be noted in view of the question of their previous home. No capulids, or gastropods of any kind, have been reported. Their absence may be attributed in part to the smallness of the collections—for the entire absence of gastropods is highly improbable—but their presence in great abundance, as in the Helderberg and Oriskany faunas, is equally improbable, and the most reasonable conclusion is that the gastropods were but an inferior element in the James Bay fauna, and that the large gastropodous factor of the Onondaga of the interior sea was derived from the Oriskany fauna already in possession of the ground when the succeeding invasion took place. This is supported by the resemblances already noted.

We have no evidence that any of the distinctive species of the Onondaga fauna lived in the South American region, where certain of the Oriskany species lived before and where certain of the Hamilton species lived afterwards. This implies that the Onondaga fauna was not distributed in that direction. In the St. Lawrence embayment, which had played so critical a part in the evolution of the American Paleozoic life, the Onondaga fauna appears to have no distinct representation. Such traces as are present appear to be only those which might arise from the counter-migration of Onondaga tribes into this breeding-ground of migrations. There was quite certainly connection with northern Europe, because a notable number of peculiar types are common to the two regions.

The whole assemblage of life displayed in this remarkable fauna seems to be explicable by postulating a generating tract in the Hudson Bay embayment, or in some more northerly or northeasterly region, possibly on the Eurasian continent. Into this it may be assumed that a portion of the Silurian fauna retired, and underwent development by itself. This fauna, after a prolonged evolution in the northern region, during which the Helderberg and Oriskany faunas were successively occupying the interior, invaded the eastern interior sea. Upon entrance, this fauna in part displaced and in part commingled with the Oriskany fauna which then occupied the ground. Some lingering representatives of the Helderberg fauna were probably also present. This admixture of exotic and indigenous forms, evolving together under the congenial conditions of the interior sea, developed the later phases of the Onondaga fauna.

The Southern Hamilton Fauna.

The life which occupied the eastern portion of the interior sea during the earlier part of the Hamilton epoch will be best understood by calling again to mind the geographic changes which permitted the entrance of a new factor from the south and controlled the development of the whole. There appears to have been a warping of the surface by which the land at the northeast was gently lifted and its rivers rejuvenated, so that they bore much more silt into the basin than before, and this, spreading widely over the bottom, changed the deposit from limestone to shale in that part of the basin, while the formation of limestone continued as before in the western portion. This warping movement may have been accompanied and abetted by climatic and vegetal conditions favorable to silt wash. The warping appears to have gone so far at length as to close the eastern straits through which the Helderberg and Oriskany faunas had entered. In the southwestern region the warping was downward and permitted the sea to creep out upon the previous land, as shown by the overlap of the Hamilton formation. There is no positive stratigraphic proof that this went so far as to make a connection with the ocean in that direction, but this seems highly probable. It is quite obvious from the nature of the life that an oceanic connection was maintained somewhere, and there is an absence of evidence that it was maintained either to the northeast or to the north, for no Hamilton beds are found in those directions, nor are there any faunal indications of such a connection. On the other hand, the fauna contains peculiar forms found also in South America, and this fact, together with certain features of distribution within the interior, strengthens the presumption of a connection lying somewhere in the lower Mississippi tract. Unfortunately this region is very deeply buried beneath younger deposits, and a stratigraphic demonstration of the continuity of the Hamilton sediments through the supposed strait is impracticable.

Assuming that these were the physical conditions which led to its introduction, the earlier Hamilton fauna may be regarded as the result of a resident clear-water fauna contending with increasing turbidity of water on the one hand, and with the invasion of a southern fauna on the other. It involved the domestic modification of the resident fauna to fit new conditions, and the absorption and accommodation of foreign accessions, for the latter do not seem to have overpowered the former. It was not therefore so radical a transformation as that which attended the introduction of the Onondaga fauna, when the invaders were not only the master type, but were aided by a progressive physical change in their favor.

The progress of the sharks and arthrodirans.—The relics of Hamilton fish thus far recovered are less numerous than those of the previous epoch, and, like them, are largely fragmentary, but they indicate an advance in structural development. The arthrodirans reached their climax in massiveness and distinctive characters. The *Dinichthys herzeri*, the leading type, was one of the largest and most formidable fish known, with an estimated length of 20 feet, and very massive proportionately. It was armed with formidable mandibles two feet in length, which, in lieu of teeth, were developed into shear-like and beaked cutting edges that closed upon their fellows in much the way the mandibles of a turtle do. These are illustrated diagrammatically in Fig. 209. The forward portion of the body was encased in heavy armor-plates, giving great defensive as well as offensive power. Related types of less formidable aspect are also known. The sharks are most commonly represented by their teeth and highly developed fin-spines, some of the latter reaching a foot in length. In both classes the implements of warfare make up nearly the whole record, and this doubtless correctly implies the dominant state of affairs in the vertebrate kingdom.

The decline of the corals.—The corals of the Onondaga fauna lived on in some notable measure and constituted an element in the new fauna. They were adversely affected by the increased turbidity of the waters, and retired largely to the western part of the basin and declined greatly in importance.

The advance of the crinoids.—The *Echinodermata* were somewhat better represented, crinoids, cystoids, blastoids, and asteroids being present, though not generally prolific. Locally the crinoids must have been abundant, for certain limestone beds are largely composed of crinoidal remains. The Hamilton genera were usually the same as those of the preceding Onondaga epoch, but not a few additional ones appeared, a foreshadowing of the remarkable crinoidean development of the early Carboniferous period. A very peculiar form was the *Arthroacantha* (Fig. 210, *q*), which was furnished with movable spines placed miscellaneously over all the plates of the dorsal cup, and attached to the calyx by means of a ball-and-socket joint like the spines of the sea-urchins, an obvious case of parallel evolution. The cystoids reappear in feebleness in the single genus *Agelacrinus*. The blastoids increased their representatives notably, some species being similar to those of the Onondaga, while others, as the *Pentremitidea*, approached the type of the Carboniferous pentremites. One of the most peculiar of the blastoids was the irregular *Eleutherocrinus* (Fig. 210, *o* and *p*), which was unlike any earlier member of the group. Some finely preserved starfishes have been found, but they were not abundant. They followed the Paleozoic type in those features in which the later forms differ from the earlier.

The climacteric deployment of the brachiopods.—The brachiopods, true to their persistent nature, held an important place in this fauna as before. They were no less numerous individually or specifically;

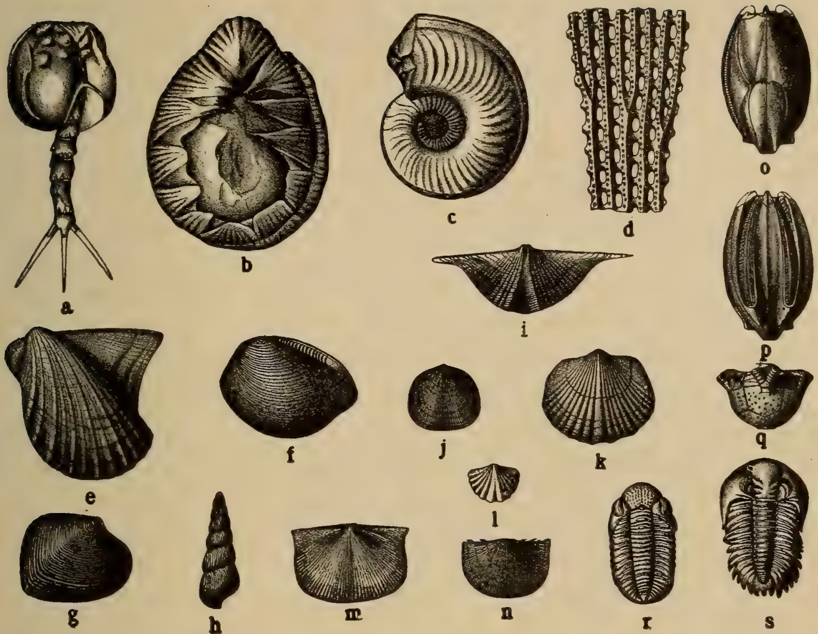

Fig. 210.—The Hamilton Fauna. *Crustacea: a*, *Echinocaris punctata* (Hall), one of the phyllocarid crustaceans, a group more highly organized than the trilobites; *b*, *Protobalanus hamiltonensis* Whitf., a sessile cirriped; one of the earliest representatives of these degenerate crustaceans. *Cephalopoda: c*, *Goniatites vanuxemi* (Hall), one of the goniatites which become more numerous in this fauna. *Bryozoa: d*, *Fenestella emaciata* Hall, one of the fenestelloid forms which became very abundant in the Middle Devonian faunas. *Pelecypoda: e*, *Pterinea flabella* (Con.); *f*, *Palæoneilo constricta* (Con.), and *g*, *Cypricardella bellistriatus* (Con.); three of the common forms of pelecypods in the Hamilton fauna. *Gastropoda: h*, *Loxonema hamiltoniæ* Hall, a high spiral shell of a form not uncommon in this fauna. *Brachiopoda: i*, *Spirifer pennatus* (Atw.), one of the long-hinge-lined spirifers more conspicuous in the Middle and Upper Devonian than elsewhere; *j*, *Rhipidomella vanuxemi* Hall, one of the orthid genera which has its great development in the Devonian; *k*, *Tropidoleptus carinatus* (Con.); *l*, *Vitulina pustulosa* Hall, and *m* and *n*, *Chonetes coronatus* (Con.), three peculiar species of brachiopods in the Hamilton fauna. They have their closest relationships with South American, Middle Devonian species. *Echinodermata: o–p*, *Eleutherocrinus cassedayi* S. and Y., a peculiar, irregular blastoid whose form has been modified by the loss of its column and its pentamerous symmetry. During life it probably rested upon one side on the sea-bottom; *q*, *Arthracantha punctobrachiata* Williams, a peculiar genus of crinoids restricted to the Middle and Upper Devonian faunas. It is characterized by the presence, on the plates of the calyx, of movable spines similar to those on the sea-urchins. *Trilobita: r*, *Phacops rana* (Greene), the most common trilobite of the Hamilton fauna. The genus, although present in the Silurian, has its great expansion in the Devonian; *s*, *Cryphæus boothi* Greene. This is one of the last of the dalmanites. Note the serrated margin of the tail, and compare with Figs. 208, *k*, and 203, *u*.

indeed their climax of deployment lies somewhere here. Their curve was so broad that its highest point is not easily fixed with exactness.

In many respects the brachiopods of this fauna were closely allied to those of the Onondaga and many species passed unchanged from the earlier into the later fauna. In most cases the changes in the environment were paralleled by changes in form that rose to specific value. The lowly inarticulate brachiopods still persisted as a minor factor, while the more highly differentiated forms attained wide diversity and high rank. The stropheodontas retained about the same relative place, waning somewhat perhaps in size, though still often large. The spirifers reached a climax in the extension of their hinge-lines (Fig. 210, *i*). This extension is particularly characteristic of the Hamilton epoch, though a feature of the Devonian generally. The geological series perhaps presents no simpler or more obtrusive character by which a formation may be identified than these excessively broad-winged spirifers. Some specimens had a breadth along the hinge-line four or five times as great as the length of their shells, if breadth may be said to be greater than length in any case. The *Orthis* family, once so prominent, had fallen to a very subordinate place. The productids increased notably, and were obviously advancing toward their great expansion in the Carboniferous period. The meristoids fell away and were nearing the close of their career. The loop-bearers of the *Terebratula* and *Cryptonella* types increased. The persistent *Rhynchonella* family was represented by species wonderfully prolific in individuals. The pentamerids made but a feeble showing. Several species of extreme interest and significance invite special notice, among which are *Tropidoleptus carinatus* (Fig. 210, *k*), *Vitulina pustulosa* (Fig. 210, *l*), and *Chonetes coronatus* (Fig. 210, *m* and *n*). The first two belong to peculiar genera not previously found in the interior basin. Apparently they could not have been derived from any of the preceding inhabitants of the region. The third species belonged to a genus represented by other species that previously lived in the region, but this particular species is peculiar, and does not give signs of any near kinship to the previously resident members of the genus. All these forms were locally abundant in the Hamilton assemblage. They bear the marks of immigrants, however, and a search for their former home and relatives reveals the fact that in South America the same species, or closely allied ones, lived in abundance, and that they are there preserved in beds which overlie beds containing Oriskany forms. This means that they lived in South America at a time just previous to or nearly identical with their appearance in the North American fauna. That they were immigrants from the south is the almost necessary inference.

The advance of the cephalopods.—The mollusks were an interesting factor of the Hamilton fauna. The new lobate-sutured cephalopods, the goniatites, which were represented by a single known species in the previous fauna, now appeared in six species. One of these, *Goniatites vanuxemi* (Fig. 210, *c*) reached the notable size of a foot in diameter. The *Nautilus* regained the prominence it had lost since the Niagara epoch and appeared in forms rivaling the large goniatites, and some of them began to exhibit the node-like ornamental expansions of the shell which became so conspicuous in the later Carboniferous faunas. It seems to have replaced the more loosely coiled *Cyrtoceras* and *Gyroceras* of the previous fauna. The straight forms were present and were closely allied to those of the Onondaga epoch.

The abundance of the pelecypods.—The silty bottoms favored the pelecypods, and they developed in great abundance, the number of recognized species approaching 200. The aviculids of the obliquely winged type were the most conspicuous and characteristic. A representative form is illustrated in Fig. 210, *e*. A part of the pelecypods were obviously derived from Onondagan predecessors, while others were peculiarly Hamilton types, either immigrants, or forms so widely different from Onondagan forms that their parentage is unrecognizable.

The subordinate place of the gastropods. —Though fairly abundant, the gastropods were quite inferior to the pelecypods in numbers. The genera were almost entirely the same as in the Onondaga epoch, though the species were largely new. The capulids were still abundant, but by no means so plentiful as in the preceding faunas. The pteropods, again on the ascendant, were represented by *Conularia*, tentaculites, and a minute *Styliola* which largely formed certain thin beds of limestone, as the tentaculites had previously done.

Other features.—The Hamilton trilobites differed notably from the Onondagan in being much inferior in numbers and much less ornamented. The dalmanites was present, but in relatively modest garb. As an offset, the other crustaceans were more amply represented by the phyllocarids (Fig. 210, *a*) and cirripeds (Fig. 210, *b*). Among the latter were the first known barnacles of the modern sessile type. In losing its pedicel, and in fixing itself immovably on other objects, it became a degenerate type, but it found an unworthy place for itself to which it has hung with wonderful persistency, not unlike the debased human class which it has come to typify, for it has lived through all the ages since, and still shows no signs of extinction.

The Northwestern Hamilton Fauna.

While the preceding fauna was developing in the eastern interior sea and apparently receiving contributions from more southerly coasts, another fauna was evolving on somewhat different lines in a sea that appears to have overspread a large tract in the northwestern interior. This sea embraced portions of Missouri, Iowa, Manitoba, and the Mackenzie valley. It doubtless had its oceanic connection at the north or northwest. It does not appear to have had any connection with the ocean to the south in the earlier stages. It seems to have

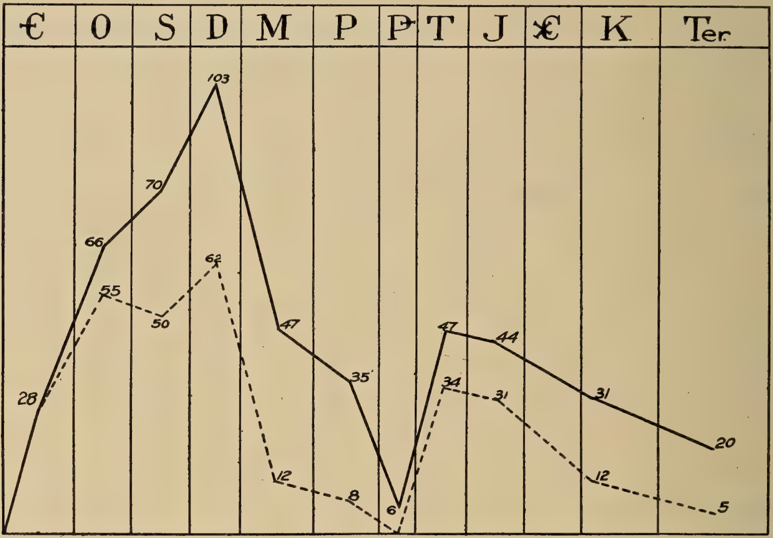

FIG. 211.—This curve is compiled chiefly from data contained in Schuchert's Synopsis of American Fossil Brachiopoda, and represents approximately the state of our present knowledge of the geologic range of the genera of fossil Brachiopoda. The broken line represents the number of new genera initiated during the successive geologic periods; the full line represents the total number of genera present; and the difference between the two represents the number of genera which have passed over from the preceding period.

gradually extended itself to the southward and at length to have joined the eastern sea across the tract stretching from the old lands of Wisconsin to the similar old lands of Missouri which had in the earlier stages formed a separating isthmus, but which at length became submerged by the advance of the seas on either hand. This northwestern fauna was closely allied to the Middle Devonian fauna of eastern and central Europe. So close indeed is the similarity that the inference is forced that there was free intercommunication between the two regions. The prolonged sea-arm that reached down the great interior valley of the northwest was perhaps no more than an *eastern* extension of the Eurasian Middle Devonian province.[1] The extension of this great sea-arm took place late in the Devonian period, for the strata bearing its peculiar life lie directly on the older formations in Missouri, Iowa, and Minnesota, with no Lower Devonian beds between, showing that the sea crept in after the earlier Devonian epochs had passed. The brachiopods furnish the most decisive evidence respecting the relations and genesis of this northwestern fauna.

Brachiopods as evidence of geographic connections.—In Europe there is a horizon so well marked by *Hypothyris* (*Rhynchonella*) *cuboides* that it is known as the "cuboides zone" and has a notable place in the literature of the subject under that name.[2] This species also occurs in eastern Asia (China), in northwestern America (Mackenzie valley), in western America (Great Basin), and in the American interior, as far east as New York. To show how well the peculiarities of this form are held through this wide distribution, figures of typical individuals from England (Fig. 212, *h*), Russia (Fig. 212, *f*), China (Fig. 212, *g*), the Great Basin (Fig. 212, *i*), and New York (Fig. 212, *e*) are arranged side by side. Their close similarity is very notable. *Spirifer disjunctus* is another brachiopod of similar range, illustrations of which from England, China, Mackenzie valley, and New York are arranged for comparison (Fig. 212, *a*, *b*, *c*, and *d*). *Schizophoria* (*Orthis*) *striatula* is still another species common to Europe, Asia, and different parts of America, and is illustrated by specimens from England, China, Mackenzie valley, Nevada, Iowa, and New York (Fig. 212, *j*, *k*, *l*, *m*, *n*, and *o*). *Gypidula comis* from Iowa and China is illustrated by Fig. 212, *p* and *q*, and *Spirifer tullius* by specimens from New York and Mackenzie valley (Fig. 212, *r* and *s*). These strikingly illustrate the community of this wide-ranging fauna, and its close approach to a cosmopolitan fauna. Now none of these species had any representative at all closely allied to it in the southern Hamilton, nor are there any species in it from which these forms could probably have been derived. On the other hand, allied forms have been found in England, Belgium, France, Germany, Russia, Persia, and China. This seems to make it clear that the derivation was from that quarter, and that, while the American northwestern fauna had close connection with the Eurasian continent, it had no previous migratory relations with the eastern and southern Hamilton province. This is further strengthened by the fact that while the latter had species of South American origin, none of these latter are found in the northwestern fauna previous to the joining of the two provinces at the close of this stage. Wide-ranging as both the Hamilton faunas were, they had not yet entirely escaped from provincial limitations.

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[1] Weller, Journ. of Geol., Vol. VI, p. 306.

[2] Williams, The Cuboides Zone and its Fauna. Bull. G. S. A., Vol. I, p. 481, 1890.

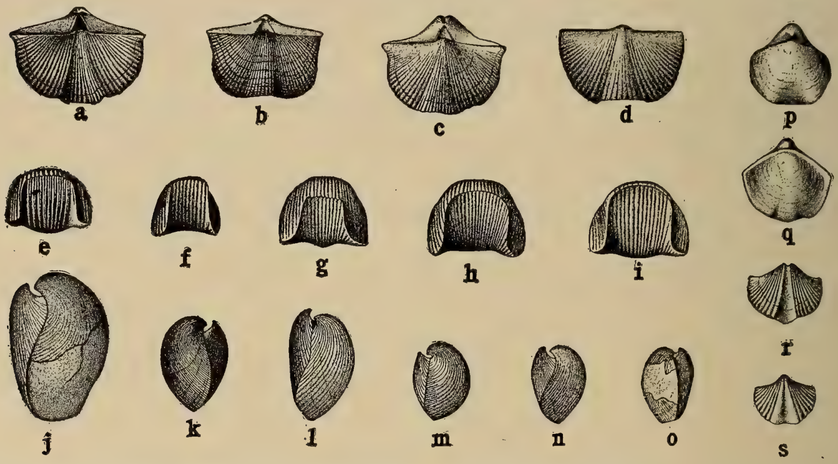

Fig. 212.—Upper Devonian Brachiopoda, showing the geographic distribution of five species: *Spirifer disjunctus* Sow.; *a*, England; *b*, China; *c*, Mackenzie valley; *d*, New York. *Hypothyris cuboides* (Sow.); *e*, New York; *f*, Russia; *g*, China; *h*, England; *i*, Great Basin. *Schizophoria striatula* (Schl.); *j*, Mackenzie valley; *k*, New York; *l*, England; *m*, China; *n*, Iowa; *o*, Nevada. *Gypidula comis* (Owen); *p*, Iowa; *q*, China. *Spirifer tullius* Hall; *r*, New York; *s*, Mackenzie valley.

The corals of the northwestern Hamilton fauna were of the Onondaga type, which seems to indicate that at an earlier stage the Onondaga fauna and the ancestors of the northwestern Hamilton fauna came into communication, as might well have happened from the northern distribution of both. The corals of the northwestern Hamilton fauna were more abundant than those of the southern Hamilton fauna, but much inferior to those of the Onondaga.

The echinoderms were a minor factor, as were also the trilobites and bryozoans. The pelecypods were less abundant than those of the southern Hamilton and different from them. Gastropods were present, but not important, and the same may be said of the cephalopods.

Some notable fish remains have been found in Iowa, but they are quite different from these of the eastern area, although perhaps derived from them by westward counter-migration, after the communication between the provinces was established.

In the later part of the Hamilton epoch, when the southern and northwestern seas became confluent, the northwestern fauna invaded and overran the eastern and southern territory, and a new fauna developed from the commingling of the members of the two. This leads on to the closing, more cosmopolitan phase of Devonian life in the interior sea, the Chemung fauna.

The Later Devonian (Chemung) Fauna.

The commingling and conflict which attended the invasion of the eastern and southern interior sea by the northwestern fauna may be regarded as the initial and controlling event in the evolution of the Upper Devonian fauna. As in the case of the Onondaga invasion, the northern fauna proved the more virile and gave character to the composite fauna that resulted from the extinction of the weaker species and the fusion of the remaining invaders and invaded. The stratigraphical evidence of the invasion is first caught on the western border of the invaded sea in the fauna of the Hamilton at Milwaukee. The northwestern invaders appear first in the eastern part of the basin in the Tully limestone of New York, where the detection of the significance of the fauna is due to the critical studies of H. S. Williams.

The influence of faunal and physical conditions.—From the fact that the sediments of the time were predominantly silts and sands, only a slight and precarious submersion of the occupied portions of the continental platform is inferred, and this was not a condition altogether favorable to the evolution of a general fauna of the first order, and the local conditions were effectively impressed on the fauna. In the interior basin there were three dominant factors: (1) the resident southern Hamilton fauna, (2) the invading northwestern fauna, and (3) the shallow and rather turbid waters in which these faunas met and merged.

The last of these factors expressed itself in a notable rarity of corals to which the impurity of the waters was uncongenial. In a lesser degree, this was true of the crinoids, but they none the less exhibited rather surprising powers of resistance or of adaptation, since all the orders were represented. Cystoids and blastoids have not been found, and starfishes were rare. The first known American echinoid appeared in the Chemung, though in Europe the type had appeared as early as the Ordovician.

The brachiopods best express the outcome of the commingling of the resident and immigrant faunas. They distinctly indicate two groups: (1) an indigenous class which had developed from the preceding resident fauna of the basin; and (2) an exotic class which was derived from the immigrants and bore European characters. Among those of native descent were *Atrypa reticularis, Atrypa hystrix, Cyrtina hamiltonensis, Tropidoleptus carinatus,* and probably certain species of *Stropheodonta* and *Productella.* Among the prominent immigrants were those previously discussed and illustrated in Fig. 212. The foreign group was more conspicuous than the native. The reverse, however, was the case with the mollusks. The pelecypods were numerous, but not so abundant as in the preceding epochs. The majority appear to have been descendants of the resident bivalves. Distinct foreign relationships have not as yet been satisfactorily distinguished, though some suggestive resemblances have been noted. Perhaps the bivalves were not well suited to distant migration. The gastropods were less numerous than before, and apparently local. The pteropods were represented by *Tentaculites* and *Conularia,* similar to those of the preceding faunas. The genera of the cephalopods were usually the same as those of the southern Hamilton, though the species were mainly new; but in the goniatite genus *Manticoceras,* which is highly characteristic of certain Portage beds in western New York, there was a conspicuous Eurasian immigrant element from the northwest, as notable as that of the "cuboides" fauna.[1]

The marine fishes of the late Devonian are not very abundantly represented in present collections, and can only be characterized with some reserve. They seem to have been of the same general types as in the preceding epoch, but with a decline in the singular arthrodirans, an increase in the sharks, and a continuation of the ganoids without assignable change.

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[1] J. M. Clarke, 16th Ann. Rep. N. Y. St. Geol. for 1896, pp. 22–161.

The pelagic and abysmal life of the Devonian.—Concerning the pelagic life of the Devonian nothing is known except as it may be obscurely suggested by the floating forms that were entrapped in the sediments of the shallow-water zone, or that found their way into the interior seas, and this element does not admit of satisfactory interpretation.

Respecting the abysmal life nothing is known. The strata reveal no clear case of beds laid down on the abysmal bottom of the Devonian ocean and subsequently lifted to an accessible position. It is therefore important to keep ever in mind the limitations to which all statements respecting the marine life of this period, if not of all geological periods, are subject.

Marine vegetation.—As usual, the record of the marine plants is too imperfect for satisfactory discussion. There are evidences of algæ as before, and they appear to have been well deployed, and theoretically they must have been abundant. Sections of what are interpreted as the stems of a gigantic seaweed (*Nematophycus*), sometimes reaching three feet in diameter, have been found. They perhaps mark the dimensional climax of this form.

The Devonian Fauna in the Great Basin Area.

In the region which constitutes the Great Basin of the west, a large area seems to have been occupied continuously by the sea from about the beginning of the Devonian time to the later part of the Carboniferous period. It seems to have been measurably free from both the physical and the biological changes which gave such diversity to the eastern provinces. The fauna seems to have had a slow continuous evolution, fed, it would appear, from time to time by accessions from the two northern provinces or from some source with which they were connected. None of the distinctive South American forms appeared in it, nor any of the peculiar Helderberg or Oriskany forms. It is inferred, therefore, that it was disconnected from these provinces throughout the whole Devonian period. On the other hand, a notable number of species were common to it and to the northwestern province, as also to the interior province after it had been invaded by the Onondaga and northwestern Hamilton faunas. While its fauna is not yet well enough known to sanction the drawing of final conclusions, it bids fair to offer as fine an example of a steady uninterrupted development of a provincial fauna as does the eastern province of the fluctuating and militant development of a composite fauna out of provincial invasions.

The western fauna has, as now known, few salient features. The corals which were present in considerable abundance were largely identical or closely allied to those of the Onondaga fauna of the northeast, and doubtless had a common origin, through some northern connection. Brachiopods were, as might be expected, the leading element. Several species were identical with those of the Onondaga fauna, and several were identical with species embraced in the northwestern Hamilton fauna. The former are found mainly in the lower horizons of the formation, and the latter in the upper. In this they seem to indicate an early communication with the sources of the Onondaga fauna and a later connection with those of the northwestern Hamilton. There were some pelecypods also that held a like relation, but the greater number seem to have been indigenous. Altogether they were rather abundant. The same may be said of the gastropods. The cephalopods, so far as known, were few and mostly indigenous. The trilobites were feebly represented and were probably all indigenous. Echinoderms have not yet been reported. Fish remains are found abundantly in certain localities.

II. THE LIFE OF THE LAND WATERS.

Principle of interpretation.—It would doubtless be as difficult to draw any sharp line between the fishes of the land waters and those of the sea in Devonian times as it is now, even if we had as complete knowledge of them, probably even more so, for the differentiation of the two classes was doubtless less complete than now. For geological purposes, however, all those fishes that were denizens of the streams and lakes, also those of the freshened waters of the estuaries, bays, and inlets on the land border, may be classed together as fishes of the land waters, for they were dependent on conditions inseparable from the land. It may fairly be assumed that when land plants, insects, and terrestrial mollusks are present in relative abundance, and true marine forms are absent, the associated fishes are land-water forms. When land plants, insects, terrestrial mollusks, and fishes are mingled with a limited selection of species that are usually marine, but which may have frequented somewhat freshened waters, the better inference is that the mixture took place in brackish waters largely surrounded by land from which the true land forms were floated in. When land plants, insects, etc., are commingled with a full group of true marine forms, the better inference is that the former were carried out to sea by floods, and that the deposit was really marine. In such an association no safe inference can be drawn relative to the habitat of the fishes, unless there is independent evidence, for they may have been true dwellers in the sea, or may have been floated out from the land streams. If these three cases occurred alone, the interpretation would be fairly easy; but it so happens that in some of the great Devonian series, certain parts of the formation embrace cases of the first or second class, while in other parts cases of the third class are presented. The better inference here is that the formation took place in part on land or in land waters, and in part in marine waters. The deposits forming to-day in the great valley of California embrace fluvial, lacustrine, and marine deposits, together with land aggradation. At a geologically distant day, only small portions of this aggregate would probably be found fossiliferous, and the evidences of these portions might be quite opposed to one another, according to the particular parts selected; but the true interpretation is obvious. This appears to be very much the state of things that is recorded in the "Old Red Sandstone" type of the Devonian deposits. In America, the Catskill deposits, or some large part of them, appear to belong to this type. It is clear that they were contemporaneous with the Chemung in part, and the opinion of Williams and others that in their total range they may even have been contemporaneous with the whole of the marine Devonian series is inherently reasonable, for there can be little doubt that there were lacustrine, fluvial, and land-aggradational deposits at all times throughout the period. The only question is whether these have been preserved and are now known. In the Canadian provinces, deposits of this kind seem to have a quite ample development. But as all these deposits were, by hypothesis, laid down in more or less local basins, no exact correlation of them is possible at present and they may best be considered together. The general faunal conception is therefore that in the Appalachian tract and in the Canadian provinces lying to the northeast of it, as well as in Great Britain and Russia, there were many lodgment basins that were progressively filled by land-wash and fresh-water sediments, and that these basins were the home of a fresh-water or brackish-water fauna, in which ostracoderms and fishes were the leading elements, and crustaceans their chief colleagues.

The remarkable deployment of the crustacean-ostracoderm-vertebrate group.—No more suggestive combination of ancient life is presented by the geological record than that which is found in these supposed fresh-water deposits. The type was foreshadowed by the eurypterids and fishes, or fish-like forms, that appeared in the closing stages of the Silurian, but the record of that time is too imperfect to disclose its deeper significance. Even with the much superior material of the Devonian period, the more profound significance is only just beginning to be realized. The center of interest is a unique group of ostracoderms, which were at first interpreted as placoderm fishes, and later classed with the jawless fishes (*Agnatha,* lampreys, etc.), but which seem now to be clearly proven[1] to be an entirely distinct class lying between the arthropods and the vertebrates, and having some of the characteristics of each, but not truly belonging to either. Their supreme interest lies in the force they give to the suggestion that the vertebrates sprang from the arthropods.

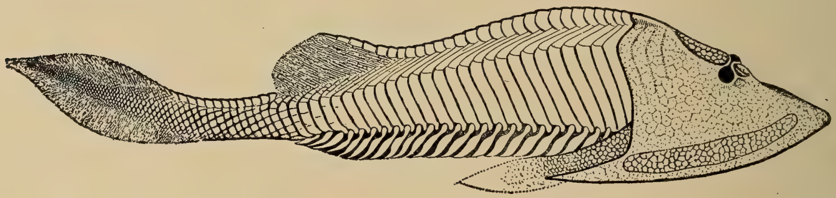

Fig. 213.—Restoration of *Cephalaspis* seen from the side. (After Patten.)

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[1] W. Patten, On the Origin of Vertebrates, with special reference to the structure of the Ostracoderms. International Zool. Cong., Berlin, 1901. On the Appenpages of *Tremataspis*, Am. Nat., XXXVII, 1903, p. 223. On the Structure of the *Pteraspidæ* and *Cephalaspidæ,* Am. Nat., XXXVII, 1903, p. 827. New Facts concerning *Bothriolepis,* Biol. Bull. No. 2, 1904, p. 113.

The ostracoderms.—The strange forms grouped under this term bear external resemblances in the head and trunk to the trilobites and king-crabs, while some of them have caudal fins and a fish-like body. Because of these last features and the presence of bone cells in the dermal armor of some members of the group, as well as their intimate association with true fishes, they have been classed as fishes until recently. But no vertebræ nor notochord has been found, nor true pectoral or pelvic appendages, nor do they possess either upper

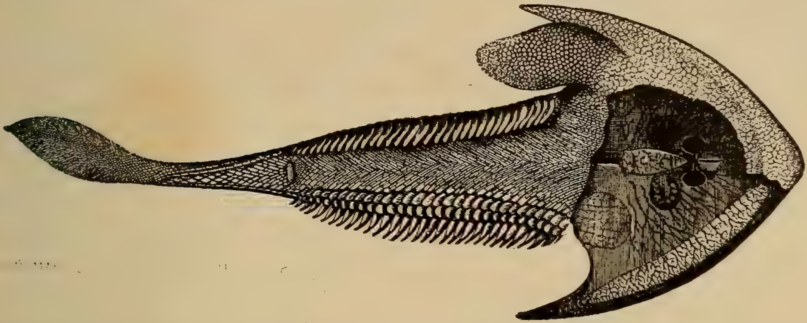
FIG. 214.—Restoration of *Cephalaspis* seen from below. A part of the ventral wall of the head is shown on the left, the rest being removed to show the inner surface of the roof of the shield. (After Patten.)

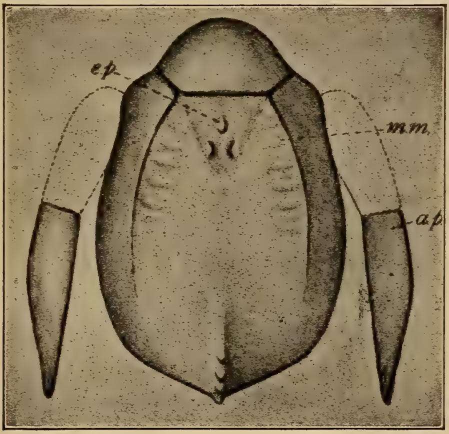

FIG. 215.—Restoration of the head shield of *Cyathaspis*, showing the oar-like appendages, *ap*, the three median eye-pits, *ep*, and the paired muscle markings, *mm*, sometimes regarded as gill-pouches. (After Patten.)

or lower jaws of the vertebrate type. On the contrary each jaw consists of two separate parts which act upon one another, not vertically, in vertebrate fashion, but *laterally*, as in arthropods. This is especially true of the upper jaw. While perhaps they should remain under the broad mantle of the term *Chordata*, they must apparently be removed from the true vertebrates to a new class.

The forms which show most strikingly the arthropodian anterior and the vertebrate-like posterior, are the cephalaspids (head-shield) illustrated in Figs. 213 and 214, restorations by Patten. The broad shovel-like head, with the eyes close together on the central ridge, is interpreted as an adaptation to plowing in the mud, half-buried, after the fashion of the modern king-crab (*Limulus*), to which the cephalaspids are believed to have borne more than a superficial resemblance. The eyes were protected by a thin coating of hard material continuous with the outer layer of the shield. The large, segmentally arranged trunk-scales, the tail and the fins, are decidedly fish-like, while the projected side angles of the shield (*cornua*), so trilobite-like in aspect, as well as the cephalic appendages, are curious features that have awakened much discussion; as have also the fringing appendages along the side of the body.

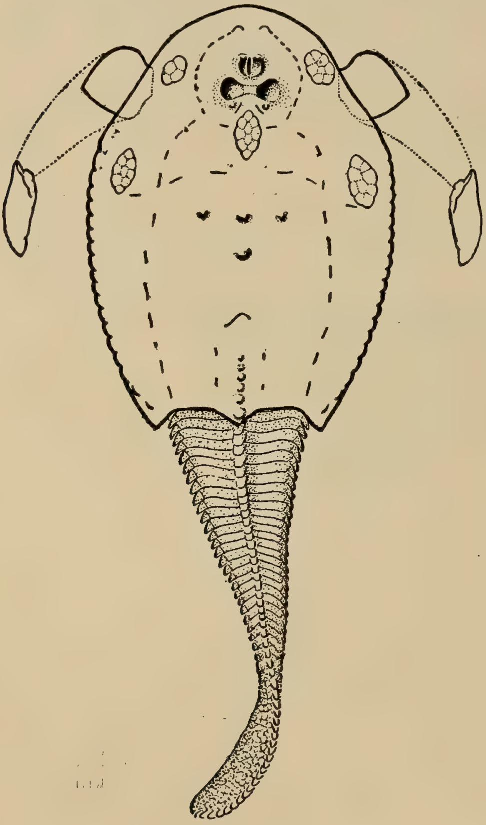

FIG. 216.—Reconstruction of the head and trunk of *Trematapis*, seen from above. Natural size. (After Patten.)

The *Pteraspis*, the earliest of these curious creatures to appear in America (Salina), is still imperfectly known and the subject of pronounced differences of interpretation. The *Cyathaspis*, Fig. 215, referred to this family, seems to throw much light on its relations in that it possessed oar-like appendages, median eye-pits, and muscular markings that assist in interpreting doubtful features in the *Pteraspis*.

The *Trematapsis*, as interpreted by Patten, had a broad oval shield, with a pair of oar-like swimming appendages, and a relatively small, rather slender trunk, as illustrated in Fig. 216. As in the *Cephalaspis*, the lateral and median eyes and the olfactory pit were close together on the median line, well back from the front margin.

Perhaps the most curious of all these strange creatures were the pterichthyds (winged fish), of one of which, *Bothriolepis*, an elegant restoration by Patten is shown in Fig. 217. In this the structure has been worked out in great detail from a large collection made in New Brunswick. The *Bothriolepis* had a short head with close-set lateral eyes on movable stalks, an angulated buckler, and a very slender naked trunk bearing two dorsal fins, and a tail of peculiar form. Three pits on the inner surface of the head, between the lateral eyes, indicate the presence of a trioculate median eye. There is no sign of vertebræ or of notochord, though the latter may have been present. Many anatomical features suggest relations to the arthropods on the one side, and to vertebrates on the other.

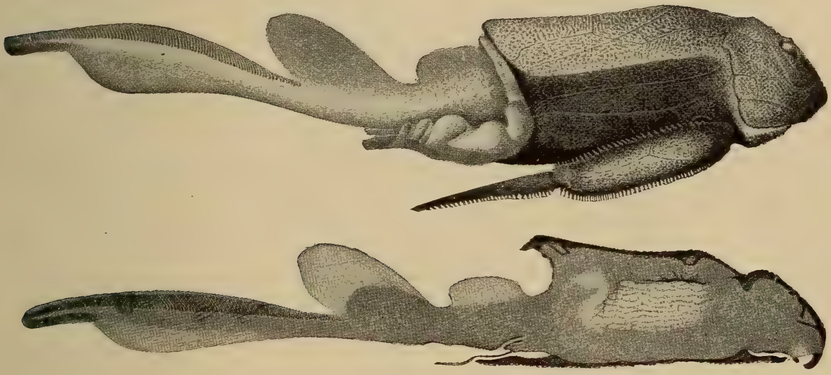

Fig. 217.—Reconstruction of *Bothriolepis*, side view. (After Patten.)

It is obvious from even the few features here noted that the ostracoderms differed greatly among themselves, and were probably already an ancient widely divergent line. Their distinct separation from the fishes puts a new phase on their place in the life series. Instead of being initial vertebrates, they formed the climax and almost the end of their own strange race, for they practically disappeared with this period. Their disappearance is not surprising in view of the development of powerful fishes, for the ostracoderms were obviously not a masterful race. Besides being small, their forms were clumsy in the main, their locomotive organs lacked flexibility and efficiency of form, and their mouth-parts were weak, and poorly situated for aggressive service, as were also their eyes. They probably plowed the soft bottoms of the sluggish waters, half-buried in the mud, above which little beside their peculiarly placed eyes and the backs of their plated bucklers were habitually exposed. They flourished in the fresh waters of the eastern Canadian provinces, as also especially in England, Scotland, Wales, and northwestern Russia. With little doubt there was a migratory zone between these regions. While the ostracoderms are sometimes reported as occurring in beds with marine fossils, there is little evidence that they were true dwellers of the open sea.

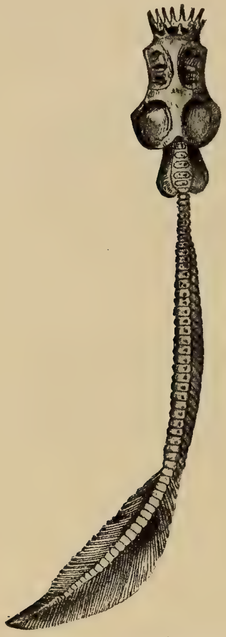

FIG. 218.—*Palæospondylus gunni*, restored by Traquair; from the Old Red Sandstone, Caithness, Scotland. (After Dean.)

The cyclostomes.—Another strange class of organisms related to the fishes, but not true fish, was represented by the singular little lamprey-like form, *Palæospondylus* (Fig. 218), which has awakened much interest because of the suggestion that it was really an ancestral lamprey, a suggestion supported by many of its characters; but opinions differ as to the real nature of this relationship. However this may be, the vertebrate idea is represented in great simplicity; a slender column of vertebræ, modified at one end into a head and finned at the other for a tail, without ribs, or paired fins, or any suggestion of paired limbs, make up the known structure. It seems to represent a quite primitive type of the vertebrates. The little creature was scarcely two inches long, and so far as known was represented by a single species only, found at Achanarras, north Scotland.

The wide deployment of the fishes.—The true fishes found in the supposed fresh-water deposits of the Devonian exceed in number and variety those found in the contemporaneous marine formations. Their relative abundance, however, changed notably during the succeeding periods until the sea fishes came to preponderate over the fresh-water fishes. Some of the leading types seem to have flourished in the fresh waters, while it is doubtful whether or not they had any real representation in the sea, though their remains are occasionally found in marine deposits. This is of interest in connection with the question of the original habitat of the vertebrates, a question to which the new views of the ostracoderms give fresh point.

Perhaps the strangest of the fishes were the arthrodirans represented by *Coccosteus* and its allies, Fig. 219. The *Coccosteus* was well protected by plates upon its head and shoulders but not on its posterior parts, of which little is known. The relations of the arthrodirans to other forms are puzzling, but most paleontologists regard them as a specialized and rather divergent branch related to the ancestors of the lung-fishes.

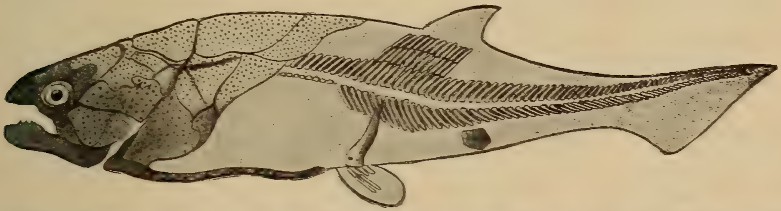

FIG. 219.—A partial restoration of *Coccosteus decipiens;* from the Old Red Sandstone of North Scotland. (After Woodward.) About one-fourth natural size.

The lung-fishes (*Dipnöi*) formed a notable feature in the fauna. This was perhaps even the time of their maximum development and specialization. It is a matter of interest that they were more abundant in the fresh-water faunas than in the marine, as it is in line with the fact that they are now wholly confined to fresh waters, being represented by a few strangely isolated forms, viz., *Ceratodus* in Australia, *Protopterus* in Africa, and *Lepidosiren* in South America. The *Dipterus* (Fig. 220), a representative form found in the Old Red Sandstone of north Scotland, had the outlines of a typical modern fish and was completely covered with scales.

The *crossopterygians* (fringe-finned ganoids), at present the most favored claimants to the parentage of the amphibians, were represented by *Holoptychius*, *Eusthenerpteron*, and their allies. These show many resemblances to the amphibians in their teeth and skull-bones, and these structural resemblances of the hard parts count for more than the physiological resemblances between the lung-fishes and the amphibians. In the *Holoptychius* (Fig. 221) the enamel of the teeth was intricately infolded, giving a dendritic structure in cross-section, as illustrated in Fig. 222, which much resembles the labyrinthodont structure of certain of the early amphibians. The holoptychians appear to have been rather rare in the early Devonian, but to have

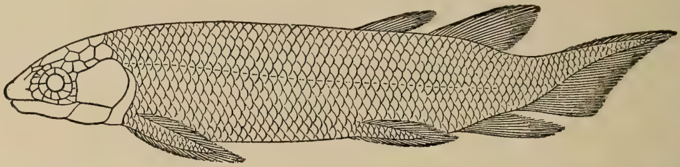

FIG. 220.—*Dipterus valenciennesi*, restoration by Traquair; from the Old Red Sandstone, North Scotland; about one-fifth natural size.

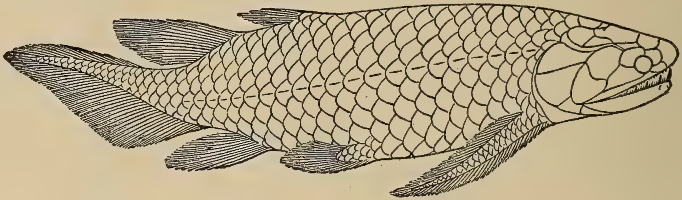

FIG. 221.—Restoration of *Holoptychius flemingi* by Traquair; about one-eighth natural size; from Old Red Sandstone, Dura Den, Scotland. (After Woodward.)

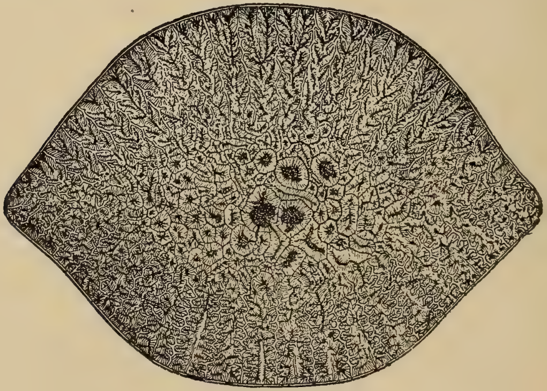

FIG. 222.—Cross-section of tooth of *Holoptychius*, much magnified. (From Smith-Woodward, after Pander.)

been dominant forms in the latter part of the period. The crossopterygians are now represented by *Polypterus* of the Nile and *Calamoichthys* of South Africa. The *Osteolepis* (Fig. 223), which was closely in the ancestral line of these modern forms, was abundant in the earlier Devonian. Like the lung-fishes, the crossopterygians appear to have been at or near the climax of their evolution in the Devonian period, though the group continued in considerable strength to the Cretaceous.

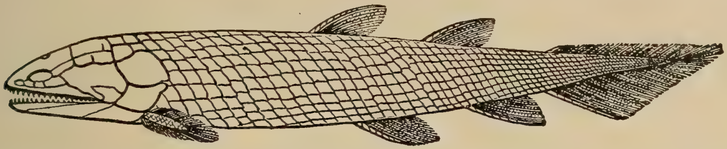

FIG. 223.—Restoration of *Osteolepis* by Pander; about one-fourth natural size; from Old Red Sandstone, Scotland. (From Dean and Woodward.)

The actinopterygians are known to have been represented at this time only by the handsome *Cheirolepis* (Fig. 224), the most primitive of the group, and remarkable among the fishes of the time for the very small size of its scales. It has been found in Scotland and in the Province of Quebec.

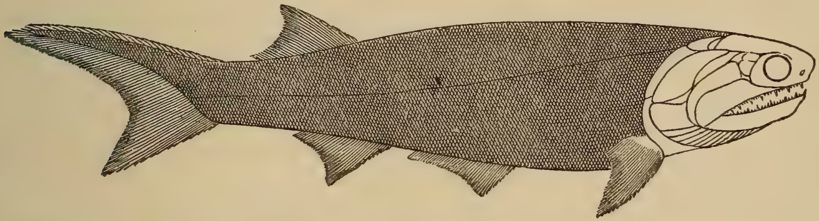

FIG. 224.—Restoration of *Cheirolepis trailli* from Old Red Sandstone, N. Scotland. About one-fifth natural size. (After Traquair and Smith-Woodward.)

The *sharks* (elasmobranchs) are now, and (unless the Paleozoic era be excepted) have been throughout known geological time, chiefly denizens of the sea; but they still occasionally live in fresh water, as in Lake Nicaragua and Lake Baikal. It seems clear that in the Devonian period they lived in the open sea, as heretofore noted, but their remains are also found in the Old Red Sandstone and in the equivalent deposits, and hence it is probable that they lived in fresh and brackish waters also. Prominent among them were the acanthodians, sharks amply armed with fin-spines (such as *Climatius* (Fig. 225) *Diplacanthus, Cheiracanthus,* etc.). There does not appear to be any clear evidence that the pavement-toothed sharks occupied the fresh waters, and this is not strange since these probably did not offer enough shell-fish to be inviting feeding-grounds.

The associated arthropods. — In view of the arthropodan relations of the ostracoderms, it is suggestive that now again, as in the Salina and in the transition beds of the European Silurian, there were gigantic eurypterids associated intimately with the ostracoderms and the fishes. Taken together, these constitute a most remarkable fauna. The *Pterygotus* now reached the extraordinary length of two meters. There were also ostracodes, phyllocarids, and phyllopods related to the *Estheria* of modern brackish waters. On the land, too, were scorpions, probably related ancestrally to the eurypterids, as well as their not distant kin, the spiders, together with myriapods and insects, probably also ancestrally related to some of the aquatic crustaceans. It has already (p. 482) been suggested that this association of arthropods and vertebrates ran back to their origin, and it may here be added that it ran on until the present day, for the fish and the arthropods (crayfish and smaller crustaceans) dominate the fresh waters, while the terrestrial vertebrates and the insecteans are only too intimate associates and contestants on the land.

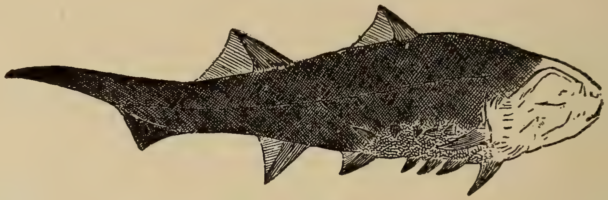

Fig. 225.—*Climatius scutiger*, natural size, from Old Red Sandstone, Scotland. (From Zittel, after Powrie.)

Fresh-water mollusks.—Shells believed to have belonged to fresh-water mollusks, and closely resembling living genera, have been found in England, Ireland, Russia, and the United States, accompanied by land plants and by fishes. Some traces of what are supposed to have been fresh-water plants have been found, but as yet little is known of the aquatic vegetation.

III. THE LAND LIFE.

It is not possible to follow the evolution of the land life with even such partial continuity as has been attempted with the marine life, for the record is much more imperfect and its interpretation more uncertain. The known life consisted of land plants, a few snails, insects, myriapods and scorpions, and mere traces of amphibians.

The land plants.—The dominant element, and the basal one as well, was the vegetation; but there are good reasons to think that its preservation was relatively the poorest. In the early stages of its evolution, vegetation was doubtless more perishable than later, from having acquired less mineral stiffening and less protective investiture of bark, husks, nut-shells, and other less perishable parts; but even in their best estate, plant tissues are less well fitted for fossilization than the shells and skeletons of animals. To this, very adverse terrestrial conditions are added. The normal fate of upland plants is to perish where they grow, and their fossilization is usually prohibited by the constant denudation of the surface. If any part of an upland plant escapes its normal fate, it undergoes usually various contingencies of decay, consumption, combustion, and other forms of destruction, before it reaches a place of sedimentation. If, escaping these, it reaches a lake or the sea, its lightness tends to keep it afloat and render it peculiarly susceptible to shore action and to different forms of organic attack. If it survives these, it is liable to be buried near the shore where subsequent denudation is most likely to cut it away, for the extreme borders of nearly all strata, except in cases of unconformable overlap, are denuded.

In the case of lowland vegetation the chances of prompt burial and preservation are much better, but even here the contingencies of subsequent denudation are large. It is only when the area of sedimentation is creeping out upon the land with relatively little shore cutting, or the low lands are undergoing permanent aggradation, that the conditions for the fossilization of land vegetation are even fairly favorable. Even when preserved, the parts of a plant are apt to be dissevered, and their re-assemblage and interpretation is difficult. It is rare that leaves, fruit, twigs, limbs, trunk, and roots are all retained together. In the case of ancient forms, especially where not closely analogous to modern types, it is more or less hazardous to attempt to restore the original plant by combining the dissevered parts of different individuals. Until these are found associated, it is usually necessary to describe and name the parts separately, and hence the possibility that different species and even genera will be founded on the separated parts of the same plant, a possibility that has been realized not infrequently. As discovery proceeds, these are detected and the nomenclature revised.

Though occasional relics of land plants have been found in the Silurian and earlier systems, it was not until the Devonian that land vegetation was fairly well preserved, but, for the reasons just adduced, it is by no means safe to assume that prolific land vegetation had not long clothed the surface, and that, perhaps, of a somewhat advanced order. Physical reasons for assuming a vegetal protection of the surface as far back as Proterozoic times have already been presented. The study of the Devonian and Carboniferous plants shows that they were widely differentiated, so much so that their ancestral relations are uncertain, which is best explained by a long previous history. The alternative is to suppose a very rapid evolution attended by an equally rapid extinction of the intermediate forms and of the residual structures that usually linger long to mark the course of evolution. This alternative is, however, preferred by some authors.

The larger part of the Devonian plants preserved were buried in inland basins, sometimes mingled with the fossils of fresh-water animals. Of the upland vegetation little or nothing is known. The lowland forms may have spread over the uplands in greater or less degree, or a very different and quite unknown vegetation may have prevailed there. Comparatively few forms have been found in the earlier Devonian formations and the apparent evolution during the period is very marked, but it is doubtful whether this represents much more than improved preservation, for the types do not converge rapidly when traced backwards as though they had originated within the period, nor do they diverge rapidly as traced on to the Carboniferous period. The Devonian types were nearly the same as those of the Carboniferous, and as the latter are much better represented in the Coal flora, their special description and illustration may be deferred with advantage until the discussion of that period.

The dominant Devonian forms were *pteridophytes* (ferns and their allies) and the lower *gymnosperms*.[1] The angiospermous flowering plants were not represented, so far as known.

The record of the lower plant groups (on the land) is almost negative. There is no evidence of liverworts or mosses (*Bryophytes*) nor of terrestrial algæ and fungi (*Thallophytes*), except that, interestingly enough, bacteria (both *bacillus* and *micrococcus*) have been reported.[2] The identification of such simple forms in fossilized woody tissue at so ancient a period is remarkable, but the presence of bacteria is altogether probable, for there is good reason to think that the decay of vegetation was then, as now, accelerated by bacterial action. Otherwise the vegetal record should be more perfect.

The pteridophytes were represented in nearly every division. Among the *Filicales* there were true ferns (*Filices*), and apparently also forms intermediate between ferns and cycads (*Cycadofilices, Pteridospermæ*). The *Equisetales* were represented by calamarians; the *Sphenophyllales* by the type genus *Sphenophyllum*, while the *Lycopodiales* were present in the form of *Lepidodendron* and possibly *Sigillaria*, reported by some authors but questioned by others. The spermatophytes, on the other hand, seem to have been represented only by their lower division, the gymnosperms, and these perhaps only by *Cordaites*, though conifers and ginkgos have been reported. The identifications are, however, questioned.

The general aspect of the ferns was already like that of the existing forms, but the other families were archaic and peculiar. It is not a little singular that forms seemingly so delicate as the ferns should have been among the most persistent and least modified of terrestrial plants. Notwithstanding their relatively modern aspect, they were archaic in many features, and embraced a much wider range of characters than at present.[3] The larger number were herbaceous, but tree-ferns (*Psaronius*), not unlike those now living in the tropics, were present. The ferns were already so far advanced in evolution that little has yet been learned from them relative to their ancestral relations. They are thought to have been the progenitors of the *Cycadofilices* (*Pteridospermæ*), and through them of the cycads and of most or all the other gymnosperms; but on this point there is not as yet complete unanimity of opinion. In numbers, the ferns or fern-like forms appear to have surpassed all others.

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[1] For classification see Vol. I, p. 653.

[2] Renault, Ann. Sci. Notes, Vol. II, 1896. See also Steward, Fossil Plants, 1898, pp. 133–138.

[3] D. H. Scott, Studies in Fossil Botany, p. 506.

The forest element was chiefly due to the calamites, gigantic ancestors of the horsetails, to the lepidodendrons, gigantic ancestors of the club-mosses, and to the cordaites, an extinct group of gymnospermous type. All of these trees were so much better developed in the Coal flora, where they reached their climax, that their discussion may advantageously be deferred.

There were not a few forms whose relations have not been made out satisfactorily from the imperfect material. Among them are those known as *psilophyton* and *ptilophyton*.

The insects.—The air was partially peopled by insects at this time. Numerous wings and other fragments have been found, chiefly near St. Johns, New Brunswick, and these have been described and interpreted by Scudder.[1] The relics indicate that the insects were of archaic and synthetic types most nearly allied to modern neuropters and orthopters, but they combined characters now found in different orders. The representatives of neuropterous aspect seem to have been related to the mayflies (*Ephemera*), whose lives are spent chiefly in water, the winged condition being assumed for a short period only. If this were true of the ancient forms, they should be regarded as aquatic rather than as aërial denizens, and scarcely as terrestrial at all. But the imperfect relics perhaps do not warrant pursuing these considerations. Fig. 226 shows the wing structure of *Platephemera antiqua*, a large species with a spread of wing of perhaps five inches. That

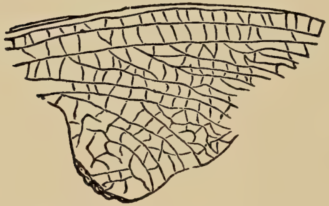

FIG. 226.—*Platephemera antiqua*, Sc., St. Johns, N. B. (After Scudder.)

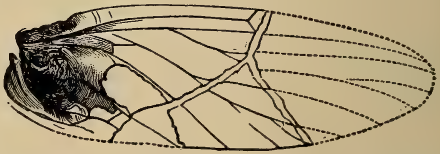

FIG. 227.—*Xenoneura antiquorum*, Sc. From St. Johns, N. B. (After Scudder.)

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[1] A list is given in Bull. No. 71, U. S. Geol. Surv., 1891. Question has been raised as to the Devonian age of these.

some at least of the Devonian insects were terrestrial vegetable feeders is perhaps indicated by Scudder's identification of a stridulating call-organ attached to the wing of *Xenoneura antiquorum* which implies not only an arboreal habit but an advanced evolution of the hearing organs. Fig. 227 illustrates the wing structure of this species, and shows, imperfectly, the supposed stridulating organ. As cockroaches had appeared in the Silurian, they also were probably present.

Other terrestrial forms.—Myriapods, arachnoids, and a scorpion are reported from plant-beds in New Brunswick, referred by Dawson and others to the Devonian. Myriapods were present in England in at least two genera, according to Peach.[1] Terrestrial mollusks are also reported from New Brunswick.

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[1] Proc. Roy. Phys. Soc. Edin., Vol. VII, 1882, p. 179.

CHAPTER IX.

THE MISSISSIPPIAN (EARLY CARBONIFEROUS) PERIOD.

The time from the close of the Devonian period to the end of the Paleozoic era was formerly regarded as a single period. Since the formations of this period included many important coal-beds, the name Carboniferous was assigned to it. During the course of the Carboniferous period, according to the old definition, the following general sequence of events seems to have taken place:

(1) Early in the period there was an expansion of the interior epicontinental sea, especially to the westward, decreasing, correspondingly, the area of the land (Fig. 228). The deposits made in the sea during this stage not only overlap the Devonian beds at many points, but rest on strata older than the Devonian. The early Carboniferous beds probably underlie the Great Plains, where the Devonian system is believed to be absent, thus pointing to wide-spread submergence in this direction. This interval of sea-transgression constitutes the first major division of the Carboniferous period, as generally defined, and has been variously known as the *Subcarboniferous*, *Lower Carboniferous*, and *Mississippian.* It was brought to a close by wide-spread emergence of the area where sedimentation had been in progress.

(2) During the next division of the period, as the term Carboniferous has been used generally, the sea was at first absent from much of the area between the Appalachian mountains on the east and the one-hundredth meridian on the west. This epoch of emergence seems to have been followed by a brief epoch of submergence, and this by a long interval during which the area of the eastern interior maintained a halting attitude, being now slightly above the sea-level and now slightly below it. This period of oscillation constitutes the second

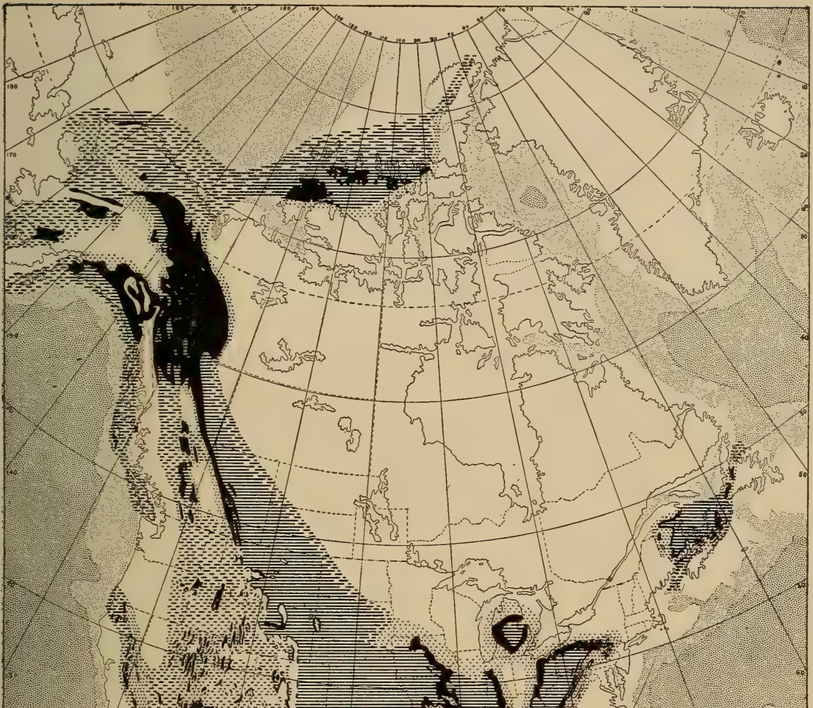

FIG. 228.—Map showing the areas, in black, where the Mississippian system appears at surface. The map also shows where the Mississippian system is thought to exist, though buried (the lined areas), and the areas from which it is thought to have been removed by erosion (the dotted areas). By inference, also, the map shows the relations of land and water during the Mississippian period.

great division of the old Carboniferous period, and has been variously designated *Carboniferous, Coal Measures, Upper Carboniferous,* and *Pennsylvanian.* West of the Great Plains this second division was, like the first, a time of wide-spread submergence.

(3) The third division of the period, as formerly defined, was characterized by a notable deformative movement, which resulted, toward the close of the period, in the folding of the Appalachian mountains, and less pronounced deformations elsewhere. During the earlier part of this movement the record shows merely a general withdrawal of the sea. Lakes (some of them salt) and partially enclosed seas were developed at various points where the open sea had been. Nearly the entire top of the true continental platform seems to have emerged by the close of the period, and to have suffered more deformation than had occurred at any time since the beginning of the Cambrian period. This division of time is known as the *Permian.*

The general relations of land and water in the middle latitudes of the eastern part of the continent during the three divisions of time mentioned above may be roughly illustrated by Fig. 229.

There has long been doubt as to the propriety of regarding the Permian as a part of the Carboniferous, and though mentioned in this connection, it is here regarded as a separate period, coördinate with the Silurian, Devonian, etc.

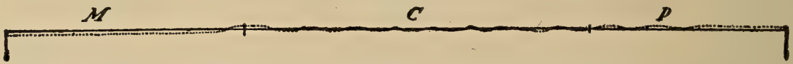

FIG. 229.—Diagram illustrating the general attitude of the middle latitudes of the eastern part of the United States, with reference to sea-level, during the Mississippian Pennsylvanian, and Permian periods. The dotted line represents land, the full line, sea level.

There seem to be sufficient reasons, also, for regarding the Mississippian or Early Carboniferous formations as a system coördinate with the Silurian, Devonian, etc., and this classification is here adopted. The reasons for this departure from the current classification will be indicated after the history of the period has been sketched.

FORMATIONS AND PHYSICAL HISTORY.

The transition from the Devonian period to the Mississippian seems to have been accomplished without notable deformative movement, so far as the larger part of North America is concerned. This is shown by the fact that the earlier formations of the Mississippian period covered most of the area where Devonian sedimentation had been in progress, and that the formations of the later system are, in general, conformable on those of the earlier. These relations hold for both the eastern and western parts of the continent. On the other hand, the Mississippian strata are more wide-spread than the Devonian, indicating that the interior sea of the Mississippian period spread somewhat more widely over the continent than that of the late Devonian period. The Catskill region, except perhaps its western part, appears to have ceased to be an area of sedimentation (compare Figs. 196 and 228), and in the eastern part of the continent, especially in New England and the Acadian region to the north, sedimentation was interrupted, for there the Carboniferous beds often overlie the upturned and eroded Devonian strata unconformably.

The Mississippian period may be looked upon as beginning with the beginning of the continental submergence which followed the Devonian period, and as ending with the emergence of considerable areas of the continent, and a corresponding restriction of the epicontinental sea (Fig. 229). From this definition of the period, it follows that the earlier beds, deposited while the advance of the sea was in progress, are more restricted in their distribution than those of a somewhat later stage, when the continent was more generally submerged beneath the epicontinental sea.

Throughout the period, the interior sea seems to have been bounded on the north, the east, and the south by land, though there were probably connections with the ocean in these directions. To the west it opened broadly, though less is known concerning its extension in that direction. In the interior sea of the east, and in the more open sea of the west, there were the conditions for varied sedimentation.

Subdivisions.

The following subdivisions of the Mississippian system are recognized in the regions indicated:

Mississippi River States.[1]	Ohio.[2]	Pennsylvania.[3]	Maryland.[4]
4. Kaskaskia or Chester	7. Maxville		
3. St. Louis	6. Logan		3. Mauch Chunk
2. Osage or Augusta (including the Burlington, Keokuk, and Warsaw)	5. Black Hand	2. Mauch Chunk	
	4. Cuyahoga		2. Greenbrier[5]
	3. Sunbury		
1. Kinderhook or Chouteau	2. Berea grit		
	1. Bedford	1. Pocono	1. Pocono

East of the Great Plains.

In the early part of the Mississippian period, when the sea was somewhat more expanded than is shown in Fig. 196 and less wide-spread than is represented in Fig. 228, the eastern edge of the sea seems to have been bordered by high land, for along the western border of Appalachia coarse sediments (sands and gravels, now Pocono sandstone and conglomerate) were gathering. The land to the north and south of the interior sea seems to have yielded finer sediments. In the area east of the Cincinnati arch, the sediments which now constitute the lower part of the Waverly series[6] were being deposited. Much of this sediment may have come from the arch itself, which may have been at first a peninsula and later an island. The area of southern Michigan[7] was a sort of bay or enclosed sea into which sediment was washed from the surrounding lands at the time the lower part of the Waverly series was being deposited east of the Cincinnati arch. The association of salt (brine) with the Michigan beds

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[1] Williams, Bull. 80, U. S. Geol. Surv., p. 169. *St. Genevieve* was the term applied by Williams to the upper part of the Mississippi system.

[2] Prosser, Jour. of Geol., Vol. IX, p. 215, and Vol. XI, p. 520. See also Am. Geol., Vol. XXXIV, p. 335.

[3] Pennsylvania Repts. and folios of U. S. Geol. Surv.

[4] O'Hara, Maryland Geol. Surv., Allegany Co., pp. 109–13.

[5] The Greenbrier is absent in eastern Pennsylvania. It comes in as a lentil of limestone farther west, and thickens southward, becoming an important formation in Virginia, largely replacing the Mauch Chunk shale. See Brownsville-Connellsville folio, U. S. Geol. Surv. (Campbell.)

[6] Geol. Surv. of Ohio, Vol. VII, pp. 503–815.

[7] Geol. Surv. of Michigan, Vol. V and Vol. VII, Pt. II, Huron County.

(Richmondville [Berea] sandstone) is significant of the climate as well as of the geography of the time.

The Kinderhook series.—West of the Cincinnati arch, the conditions of sedimentation were varied as shown by the nature of the formations. In the early stages of the period the sediments laid down were sometimes clastic and sometimes calcareous. The lowest series in the states bordering the Mississippi is commonly known as the *Kinderhook* series,[1] and is characterized by considerable variations in the character of the rock. The sedimentation seems to have varied not only in different places at the same time, but in the same place at different times. The Kinderhook series is to be looked on as representing the time when the sea was in the early stage of its advance.

The Osage or Augusta series.—A little later the waters of the Mississippi River region became clearer, and the varied sedimentation just referred to gave place to the deposition of the more nearly pure limestone. This limestone represents the second or Osage stage of the period. The sea in which this limestone was deposited extended far to the westward, probably to New Mexico on the one hand and to Montana on the other, though between the 97th meridian and the Rockies the strata then deposited are generally buried by later formations. The likeness of the fossils of the Osage limestone of the Mississippi basin to those of the corresponding formation of Europe are thought to indicate some available route of travel for marine species (especially crinoids) between these widely separated regions. What is now known of the distribution of the strata of this stage seems to point to the conclusion that this route was a northerly one, via Grinnell Land and Spitzbergen, or possibly via Alaska and Siberia (Fig. 228). Shallow water and the absence of great variations of temperature are probably the only conditions necessary for such migration as the faunas of these widely separated regions imply. The Osage series of the immediate Mississippi basin, known in Iowa and Missouri as the Augusta series, consists of several subdivisions which have local names.[2] Locally, geodes abound in the series.

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[1] For details concerning the Kinderhook of Missouri, see Weller, Jour. Geol., Vol. IX, pp. 130–48; and Keyes, Vol. VIII, pp. 313–21; and Bull. Geol. Soc. Am., Vol. XIII, pp. 267–92; for Iowa, see Calvin and Keyes, Vols. III and XIII, Iowa Geol. Surv.

[2] See reports of Missouri, Iowa, Illinois, Indiana, etc.

The rich deposits of zinc and lead ore in southwestern Missouri and eastern Kansas are chiefly in the Osage (Burlington) beds,[1] though the metallic materials were concentrated into ores at a much later time.

During the second or Osage stage of the Mississippi basin the conditions of sedimentation in Michigan seem to have remained much as in the Kinderhook stage, and the accumulation of clastic sediments continued.

East of the Cincinnati arch, which probably remained above water as an island, the deposition of clastic sediments was also continued, the sediments of eastern Ohio constituting a part of the Waverly series.[2] Still farther east, the accumulation of the sand and gravel of the first stage (Pocono) either continued, or had been succeeded by the deposition of the mud which now constitutes the Mauch Chunk shales.[3] The exact time-relation of these shales to the Osage epoch is undetermined.

While the Mauch Chunk shales succeed the Pocono sandstone of eastern Pennsylvania, with no intervening formation, there is, in western Pennsylvania, a lentil of limestone in the shales. To the south, this limestone thickens at the expense of the shale, and in Maryland[4] and Virginia constitutes a well-defined formation of limestone (Greenbrier) lying between the Pocono below and the Mauch Chunk above. The Newman limestone of more southerly regions[5] is perhaps the equivalent of the Greenbrier, or of the Greenbrier and Pocono.

The St. Louis formation.—During the third recognized stage of the period, limestone (St. Louis) deposition was continued in the Mississippi basin, but the fauna which it contains is so unlike that which had preceded as to show that geographic changes of consequence to the marine life of the interior had taken place. The changes seem to have been connected with the removal of a barrier somewhere in the west, which allowed the fauna of the Great Basin region, heretofore shut off from that of the interior, to migrate eastward, and mingle with that of the Mississippi basin. This stage marks the time of maximum Mississippian submergence, so far as the western interior is concerned (Fig. 228).

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[1] Bain, Van Hise, and Adams, 22d Ann. Rept., U. S. Geol. Surv., Pt. III.

[2] In addition to the State Reports of Ohio, see Prosser, Jour. of Geol., Vol. IX, pp. 205–31, and Vol. XI, p. 519.

[3] Probably of terrestrial origin. Barrell, G. S. A., Dec., 1906.

[4] Prosser, Jour. of Geol., Vol. IX, p. 422.

[5] See Tennessee folios.

The peculiar faunal changes which resulted from the geographic changes referred to are discussed elsewhere (p. 518). Suffice it here to say that the fauna of the St. Louis limestone of the Mississippi River region contains species which seem to have lived in the region which is now the Great Basin, but to have been unable to escape from it, at least to the eastward, until this time. Their escape and migration to the eastward at this time is the reason for believing that the barrier which had heretofore restricted them was broken down.

It was perhaps during this epoch that the Bedford limestone of Indiana, famous as a building stone, was deposited. Much of this limestone is foraminiferal, and was long mistaken for oölite. It is in the beds of this epoch, too, that many of the great limestone caves of Kentucky and southern Indiana occur.

In Michigan conditions seem to have remained much as before for beds containing salt (brine) and gypsum (Michigan series) were still in process of deposition,[1] at least during the earlier part of this epoch.

The strata east of the Cincinnati arch have not been definitely correlated with those of the third stage of the period farther west. The limestone-making conditions of the Mississippi River region may have extended eastward, south of the Cincinnati arch, to eastern Kentucky, Tennessee, and West Virginia. Farther north the sediments of this stage were predominantly clastic, and constitute the upper portion of the Waverly series. Locally, deposits of this time contain both coal and iron ore.[2] In the northern part of the Appalachians the Mauch Chunk shales [3] were in process of deposition, while other names (Pennington, Canaan,[4] etc.) are applied to the contemporaneous deposits farther south in the same mountain system. The Mauch Chunk shales contain some iron ore.

The Kaskaskia (Chester) beds.—The fourth stage of the Mississippian period, according to the classification adopted for the Mississippi basin, seems to have been marked by more restricted waters and more varied sedimentation, for sandstone and shale are sometimes associated with the limestone of this epoch. The deposits of this stage resemble in a general way those of the first stage (Kinderhook) of the period. Those were made while the sea was advancing on the land and deepening; these while it was shoaling and retreating. Both are more restricted in their distribution than the beds of the intermediate epochs. While sedimentation was general over the central Mississippi basin, there were probably changes in the relation of land and water from time to time.

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[1] Geol. Surv. of Michigan, Vol. VII, Pt. II, pp. 13–15.

[2] Geol. Surv. of Ohio, Vol. III, p. 819.

[3] The name Mauch Chunk is applied as far south as Maryland; see Jour. of Geol. Vol. IX, pp. 422–4.

[4] See Tennessee folios.

In Michigan[1] and Ohio the sediments of this stage (Maxville, upper part of Grand Rapids, see p. 500) were partly calcareous and partly clastic. Farther east the accumulating beds (upper part of Mauch Chunk) were clastic.

In summation it may be said that while the Mississippian beds are predominantly clastic east of the Cincinnati arch, they are predominantly limestone west of it, though limestone is not wanting in the east, especially in the latitude of West Virginia and Maryland, nor sandstone and shale in the Mississippi basin, especially in the first and last epochs of the period. At many points the Mississippian system carries great quantities of chert.

The sections of the Mississippian system on pp. 557–563 give some idea of its character, its range, and its relations.[2]

The Mississippian system is represented northeast of the United States, where it underlies the Coal Measures of Nova Scotia. In the coal field of this region[3] the Mississippian formations rest on Cambrian and pre-Cambrian terranes. The system consists of a thick formation (2500 feet) of more or less conglomeratic sandstone below, and of shale and limestone above. With the shale and limestone there are local beds of red sandstone and gypsum.

In the Great Plains.

Within the area of the Great Plains, the Mississippian system is known in Indian Territory[4] (part of the Caney shale, the aggregate thickness of which is about 1500 feet), in eastern Wyoming[1] (Guernsey and part of the Hartville formation), and in South Dakota[2] (Englewood and Pahasapa limestone). A section for this region is given on p. 554.

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[1] Lane, Geol. Surv. of Michigan, Vol. VII, Pt. II, pp. 13–15, and 22d Ann. Rept., U. S. Geol. Surv., Pt. III.

[2] The Mississippian (Subcarboniferous, Lower Carboniferous) is shown in many of the folios of Alabama, Georgia, Tennessee, Virginia, West Virginia, Kentucky, and Pennsylvania.

[3] Fletcher, Descriptive Note on the Sydney Coal Field, Cape Breton, N. S., 1900.

[4] Taff, Atoka, and Colgate folios, U. S. Geol. Surv.

In Indian Territory there was some disturbance at about the close of the Mississippian. The beds warped upward (relatively) at this time suffered erosion, and an extensive chert-conglomerate, the conditions for which were prepared by the interval of erosion, marks the early stage of Carboniferous proper (Pennsylvanian) deposition.

West of the Great Plains.

West of the Great Plains the Lower Carboniferous is so widely distributed as to show that the present mountain region as far west as the 117th meridian was mostly submerged, though there were numerous islands,[3] some of which occupied the position of existing mountain cores. North of the United States, marine conditions prevailed east of the Gold Ranges, and again west of those mountains. In general, submergence seems to have been more wide-spread in the west in this period than in the Pennsylvanian period which follows; but in Wyoming submergence was more general in the later period.[4]

The several stages of the epoch, as defined in the Mississippi basin, have not been separately recognized in the west, and, except for the removal (by sinking or otherwise) of the barriers which bounded the Great Basin on the east, it is not known that geographic changes of importance occurred in that region during the progress of the period. Much of the Mississippian system in the west is limestone, though clastic formations are not wanting.[5] The Mississippian formations are exposed about many of the mountains of the west, and over considerable areas outside the mountains. The system often rests on the Cambrian[1] or Ordovician,[2] as well as the Devonian, and it sometimes overlaps all earlier Paleozoic systems and lies upon the Proterozoic[3] (Algonkian), and frequently attains a thickness of several thousand feet.

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[1] W. S. T. Smith and Darton, Hartville, Wyo., folio, U. S. Geol. Surv. As classified in this folio, there is an unconformity in the Mississippian, but conformity between it and the Carboniferous proper.

[2] Darton, 21st Ann. Rept., U. S. Geol. Surv., Pt. IV, p. 503.

[3] Emmons, Bull. Geol. Soc. Am., Vol. I, pp. 263–7.

[4] Knight, Bull. 45, Wyo. Exp. Station, 1900.

[5] The Mississippian is not differentiated from the Pennsylvanian on the maps of most of the western folios of the U. S. Geol. Surv., though the two are sometimes differentiated in the text. The Carboniferous (Mississippian and Pennsylvanian) is shown in the following folios of the west: *Colorado*, Anthracite and Crested Butte, Pike's Peak, Ten Mile District and Walsenburg; *Wyoming*, Absaroka, Yellowstone and Hartville; *Montana*, Fort Benton, Little Belt, Three Forks and Livingston; *Utah*, Tintic; *Arizona*, Bisbee; and on most of the California folios.

In Colorado[4] the Mississippian is represented chiefly by limestone and dolomite (the Leadville in central Colorado, the Ouray in the San Juan region, and the Millsap in the Front range), 200 to 800 feet thick, and is one of the richest ore horizons of the state. The faunas indicate the reference of these beds to the Early Mississippian. The later beds of this system were probably removed in the post-Mississippian erosion interval.

Mississippian limestone occurs in northeastern Washington[5] and in the Canadian Rockies, where the series is between 6000 and 7000 feet thick, and includes 5100 feet of limestone.[6] The system is very generally exposed in the foot-hills of the Rocky mountains. In many parts of the west it is unconformable beneath the Upper Carboniferous or Pennsylvanian, and in many places there is an unconformity in the undifferentiated Carboniferous which may prove to divide the two systems. The system is also extensively developed in Alaska,[7] where the Carboniferous proper is less wide-spread, so far as present knowledge is concerned, and also along the Arctic Ocean farther east (Fig. 228). In the last-named region the beds are coal-bearing.[8] The Lower Carboniferous (Mississippian) has also been recognized on Melville Island.

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[1] Spring Mountain range of South Nevada, Walcott, cited by Spurr, Bull. 208, U. S. Geol. Surv., pp. 166–172; and also at various points in the Black Hills of South Dakota, Darton, 21st Ann. Rept., U. S. Geol. Surv., Pt. IV.

[2] Snake Range, Nevada, Weeks, cited by Spurr, Bull. 208, U. S. Geol. Surv., p. 32.

[3] Smith and Darton, Hartville, Wyo. folio, U. S. Geol. Surv.

[4] Eldridge, Anthracite-Crested Butte folio, U. S. Geol. Surv.; and Girty, Prof. Paper No. 16, pp. 162, 163, and 217.

[5] Landes, unpublished evidence.

[6] Dawson, Bull. Geol. Soc. Am., Vol. XII, p. 69. Willis thinks some of the beds correlated by Dawson with the Carboniferous are Algonkian; Bull. Geol. Soc. Am., Vol. XIII, pp. 323–5.

[7] Dawson, op. cit., p. 85.

[8] Dawson, Can. Geol. Surv., 1886, pp. 12R, 46–49R, and Map

Igneous Activity.

During this period, according to present determinations, there was great igneous activity in the west. West of the Gold ranges in British Columbia, the early Carboniferous is made up largely of igneous rock, with intercalated beds of clastic sediments. The area affected by vulcanism at this time, or soon after, extended from Alaska on the north to California on the south.[1] For this region the volcanic activity subsided before the close of the Pennsylvanian period.

CLOSE OF THE PERIOD.

Geographic changes which contracted the eastern interior sea to very narrow limits (Fig. 240), if they did not completely obliterate it, brought the Mississippian period to a close. Similar changes cannot be affirmed to have affected the western half of the continent to the same extent, but the tendency of recent studies is to show that geographic changes of consequence took place even in this part of the continent at this time. Evidence of this import is found in Montana [2] and farther north,[3] where the Lower Carboniferous is more wide-spread than the Upper, in British Columbia,[4] in Colorado,[5] in Indian Territory,[6] where there was perhaps notable warping, and perhaps in Utah.[7]

In some parts of the west, however, so far as now known, marine conditions prevailed uninterruptedly from the early Mississippian period to the later part of the Pennsylvanian period.

Sections of the Mississippian system,[8] at various points in the United

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[1] Dawson, op. cit., p. 85.

[2] Montana folios, U. S. Geol. Surv.

[3] Dawson, Bull. Geol. Soc. Am., Vol. XII, p. 85.

[4] Dawson, Science, March 15, 1901.

[5] Crested Butte quadrangle of the Anthracite-Crested Butte folio, U. S. Geol. Surv. See also 5 below.

[6] Colgate, I. T. folio, U. S. Geol. Surv., p. 5.

[7] Emmons, Orogenic Movements in the Rocky mountains, Bull. Geol. Soc. Am., Vol. I. Also Mono. XXVII, U. S. Geol. Surv., and Anthracite-Crested Butte folio, U. S. Geol. Surv.

[8] The Mississippian system is not represented as a separate system on the folios of the U. S. Geological Survey; but in the later folios, such as the Indiana, Latrobe, Elkland-Tioga, Masontown-Uniontown, and Brownsville-Connellsville folios of Pennsylvania, the Gaines folio of Pennsylvania-New York, the New Castle folio of Wyoming-South Dakota, and the Edgemont folio of South Dakota-Nebraska, it is represented as a major division of the Carboniferous. In the text of older folios the Mississip-

States, are given, along with the associated sections of the Pennsylvanian (Carboniferous proper), on pp. 557–563.

REASONS FOR REGARDING THE MISSISSIPPIAN A DISTINCT SYSTEM.

The withdrawal of the sea from a large part of the eastern interior at the close of the Mississippian division of the Carboniferous period exposed the newly deposited sediments to erosion. The exposure was long and the erosion considerable. At the opening of the Coal Measures period, as will be seen in the sequel, a large part of this area was again the site of deposition, and the new system rests unconformably on the Mississippian over wide areas.[1] This is true in places, and perhaps generally, in Missouri[2] (Fig. 232), Iowa[3] (Fig. 230), Kansas,[4] probably in Illinois, in Indiana[5] (Fig. 231), Kentucky[6] and

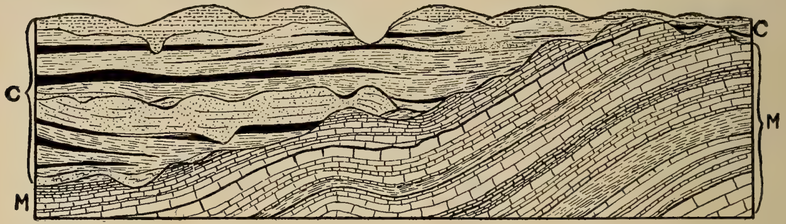

FIG. 230.—Composite diagrammatic section, showing the unconformity between the Mississippian and Pennsylvanian systems in Iowa. (Keyes, Ia. Geol. Surv.)

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pian is often clearly separated from the Pennsylvanian, though not as a separate system.

[1] Missouri Geol. Surv., Vol. VII, p. 422, and Vol. VIII, pp. 340 and 348; Iowa Geol. Surv., Vol. IV, p. 282, and Vol. I, pp. 74 and 89; the Univ. Geol. Surv. of Kans., Vol. I, pp. 17 and 147; Indiana Dept. of Geol., 20th Ann. Rept., p. 196 et seq., and 23d Ann. Rept., p. 101; Charleston, W. Va., Standing Stone, Chattanooga, Loudon. and Wartburg, Tenn.; Richmond and Loudon, Ky., and Gadsden, Ga., folios, U S.. Geol. Surv.

[2] Missouri Geol. Surv., Vol. VII, p. 424, and XII, Pt. II, pp. 31 and 209, and 22d Ann. Rept., U. S. Geol. Surv., Pt. II, p. 88.

[3] Geol. Surv. of Ia., Vol. V, p. 321, Vol. VII, pp. 79, 210, 426, 503; Vol. IX, p. 265, and Vol. XII, pp. 82, 296, and 448.

[4] Univ. Geol. Surv. of Kans., Vol. I, pp. 16 and 147.

[5] 22d Ann. Rept., Dept. of Geol. and Nat. Res., p. 17; and 23d Rept., p. 74, and Fuller, Ditney folio, U. S. Geol. Surv.

[6] Loudon and Richmond folios, U. S. Geol. Surv.

Pennsylvania,[1] West Virginia,[2] Maryland,[3] and Tennessee,[4] and the tendency of recent studies is to greatly extend it. (See also sections pp. 557 *et seq.*) In Indian Territory there was disturbance (perhaps orogenic) in the Arbuckle mountains at the close of the Mississippian period.[5]

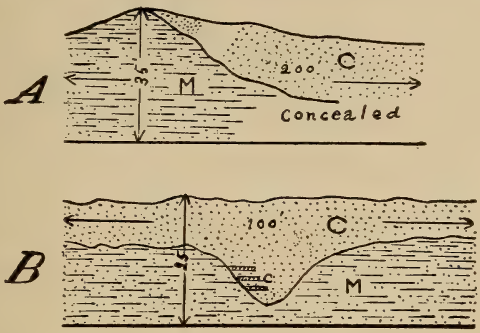

Fig. 231.—Diagrams showing unconformity between the Mississippian and Pennsylvanian systems in Indiana, *A*, at Little Pine Creek; *B*, at Turkey Run (Hopkins: Ind. Geol. Surv.)

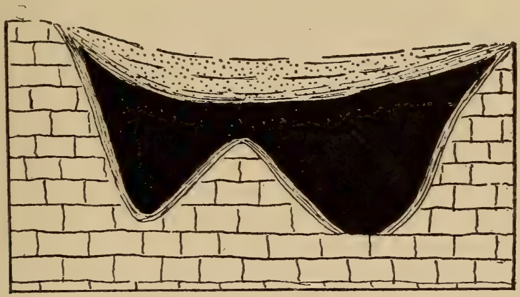

Fig. 232.—Coal in a trough excavated in Mississippian limestone. Cooper Co., Mo (Winslow, Missouri Geol. Surv.)

This wide-spread emergence, erosion, and submergence, with the accompanying unconformity of the overlying series, is just the sort of change which is here held to separate periods (not epochs). As already indicated, the geographic changes extended far beyond the eastern interior, and even beyond the Mississippi basin. In Colorado[1] there is a great break in the Carboniferous system which perhaps corresponds to that just noted. Great thicknesses of the Mississippian system were probably removed before the deposition of the Pennsylvanian formations. The relations of the strata below and above the unconformity are such as to show not only that great changes of level, but probable orogenic movements supervened. Similar changes are suggested by the relations of the earlier and later Carboniferous beds in Utah,[2] Montana,[3] and in British Columbia,[4] though their contemporaneity with those of the Mississippi basin has not been established. Even where there is no unconformity between the Lower Carboniferous and the Coal Measures, as in most of the Appalachian belt, there was a notable change in sedimentation, indicating physical changes of consequence. Nowhere else in the whole course of the Paleozoic era are so great physical changes embraced within the limits of one period. On this ground, the Mississippian (or Lower Carboniferous) might well be separated from the Pennsylvanian (Coal Measures) as a separate system. If the Mississippian and Pennsylvanian are still regarded as subdivisions of the Carboniferous period, it should be distinctly understood that these epochs, and their corresponding series of formations, are much more distinct, physically, than the epochs and series of earlier Paleozoic periods.

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[1] Fuller, Gaines (Pa.-N. Y.) folio, U. S. Geol. Surv.; Campbell, Brownsville-Connellsville (p. 7), Masontown-Uniontown (p. 7), and Elkland-Tioga (p. 3) folios.

[2] West Virginia Geol. Surv., Vol. II, p. 610 (I. C. White); Campbell, Charleston (W. Va.) folio, U. S. Geol. Surv.

[3] White (David), 20th Ann. Rept., U. S. Geol. Surv., Pt. II, and Martin, Md. Geol. Surv., Report on Garrett Co., p. 110.

[4] Maynardville, Tenn., folio, U. S. Geol. Surv. (Keith).

[5] Colgate, I. T., folio, U. S. Geol. Surv. (Taff.)

THICKNESS OF THE MISSISSIPPIAN SYSTEM.

In keeping with the variations in the sediments, the thickness of the Mississippian system is exceedingly variable. In Pennsylvania, where the group reaches its maximum development, there is a thickness of 1400 feet of sandstone (Pocono), with 3000 feet of shale (Mauch Chunk) above it; but so rapidly do the formations thin to the westward that in the western part of the state the equivalent formations have a thickness of only 300 to 600 feet. In Maryland the thickness is about 1300 feet.[1] In Ohio the sedimentary beds (Waverly shales) are rather thicker than in the adjacent parts of Pennsylvania. In the region of the Mississippi, where the system is chiefly limestone, it reaches a maximum thickness of about 1500 feet, being thinner to the north and thicker to the south, within the area of its outcrop. Even this great thickness is exceeded in West Virginia, where the limestone is more than 2000 feet thick. In Indian Territory (Sycamore limestone and Caney shale [2]) the Mississippian has a thickness of about 1800 feet, in the Black Hills of South Dakota 275 to 525 feet, in Colorado (Anthracite-Crested Butte region) 400–525 feet, and in the regions of the Grand Canyon of the Colorado in northern Arizona (Red Wall formation) 1800 feet. At any probable rate of accumulation, such great thicknesses of limestone call for very long periods of time. The duration of the period was probably as great as that of some of the preceding Paleozoic periods.

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[1] Emmons, Orogenic Movements in the Rocky Mts., Bull. Geol. Soc. Am., Vol. I; Mono. XXVII, U. S. Geol. Surv.; Anthracite-Crested Butte; and Ten Mile, Colo., folios, U. S. Geol. Surv. Also Girty, Professional Paper No. 16, U. S. Geol. Surv.

[2] See 1 above.

[3] Montana folios, U. S. Geol. Surv.

[4] Dawson, Science, March 15, 1901.

As in preceding periods, the thickest beds of the Mississippian system are in the Appalachian mountains. Here too, where the beds are thickest, they were accumulated in shallow water, suggesting either that subsidence was in progress *pari passu* with the sedimentation, or that inclined deposition took place, as the shallow-water zone crept seaward, *pari passu* with the sedimentation.

The distribution of the uncovered portions of the Mississippian beds in the eastern part of the continent is shown in black in Fig. 228. The beds themselves are of course much more extensive than their outcrops. Within the area of North America they are believed to be concealed by younger beds, largely Pennsylvanian (the lined areas of Fig. 228). They have probably been removed from considerable areas (dotted areas Fig. 228) where they were originally deposited. Like all preceding systems, the Mississippian doubtless has wide distribution beneath the sea, where it is probably thin.

THE LOWER CARBONIFEROUS [3] OF OTHER CONTINENTS.

Europe.—The post-Devonian Paleozoic systems of Europe resemble the corresponding systems of North America in some ways, and are in contrast with them in others. The formations in eastern and western Europe, as in eastern and western America, are notably unlike. In western Europe, two great series, or systems, are included under the Carboniferous, namely, (1) the Lower Carboniferous, chiefly of marine origin, and (2) the Coal Measures or Carboniferous proper, deposited partly in lagoons, marshes, and lakes, and partly in the sea. These two systems correspond, in a general way, to the Mississippian and Pennsylvanian, respectively, of eastern North America.

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[1] Prosser, Jour. of Geol., Vol. IX, pp. 422–4.

[2] Taff, Professional Paper 31, U. S. Geol. Surv.

[3] The term Lower Carboniferous is here used, instead of Mississippian, because it is the term in common use in Europe.

The relations indicated above do not hold for eastern or for southern Europe. The Upper and Lower Carboniferous formations of southern Europe are like the Mississippian and Pennsylvanian of western North America, to the extent that they are chiefly marine. The formations of eastern Europe are not closely analogous to those of any part of North America, the Lower Carboniferous being partly marine and partly non-marine and coal-bearing, while the Upper Carboniferous is largely marine.

Like the earlier Paleozoic system, the Lower Carboniferous of Europe is thicker in the western part of the continent than in the eastern, though the difference is less conspicuous. In Russia, where most of the preceding Paleozoic systems have had but a fraction of the thickness which they possess in western Europe, the Lower Carboniferous attains great development.

Though the rocks of the Lower Carboniferous series rest conformably on the Old Red Sandstone, or on other phases of the Devonian system, in many parts of Europe, they nevertheless record considerable geographic changes. The early Carboniferous formations of western Europe are of marine origin, while the Old Red Sandstone is believed to have been accumulated in inland basins. Furthermore, the distribution of the Lower Carboniferous and Devonian is somewhat unlike, the younger formation occurring at some points where the older is absent, and *vice versa*. Among other geographic changes, a very wide-spread submergence of northern lands in Europe and Asia, as well as North America, may be noted.

Fig. 233 represents the general relations of land and water in Europe during the period. Fig. 234 shows the same relations in France and its immediate surroundings in more detail. In general, the relations of the Lower Carboniferous to the Devonian indicate a somewhat wide-spread, even if slight, submergence at the opening of the Early

Carboniferous period. This, it is to be noted, corresponds with the sequence of events in North America.

The Lower Carboniferous system of western Europe, like that of North America, is largely of limestone. So true is this that the period is sometimes known as the period of the Carboniferous limestone. In Great Britain, these formations early received the name of "mountain limestone," and that name has frequently been used in connection with the corresponding formations in North America. The Lower Carboniferous limestone seems to have extended continuously from Ireland and Great Britain over northern France, where it has a thickness of nearly 2500 feet along the base of the Ardennes, through Belgium, and across the present valley of the Rhine into Westphalia. Farther east, it passes into shale, sandstone, and even conglomerate, collectively known as the *Culm*.

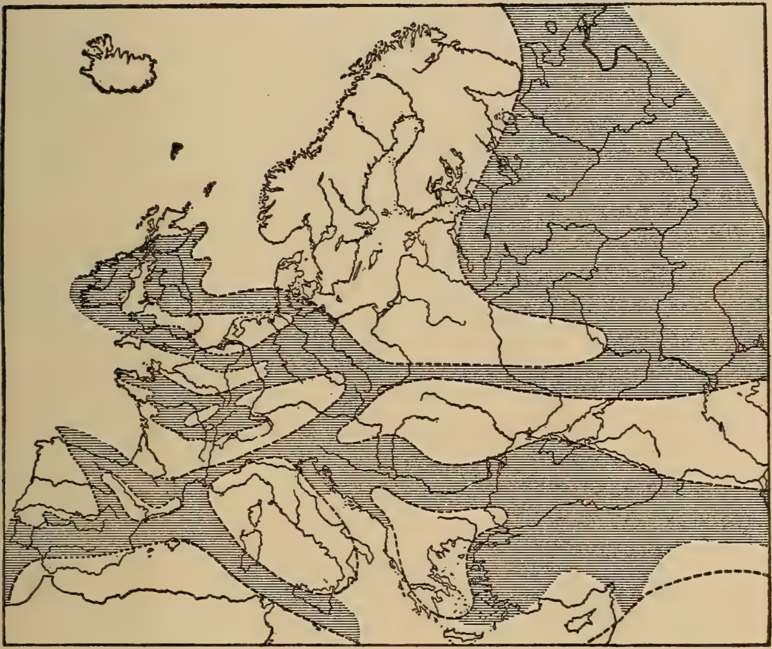

FIG. 233.—Map showing the relations of land and water in Europe in the early Carboniferous period. The shaded parts represent areas of marine deposition. (After De Lapparent.)

Limestone, however, is not the only formation of the Early Carboniferous (Mississippian) period, even in western Europe. Limestone denotes clear seas; but the borders of clear seas are often the sites of accumulation of clastic rocks, and the clear waters of the early Carboniferous sea which extended from Ireland to the north of Europe were bordered by shores along which mud, gravel, and sand were depositing. In the north of Britain, for example, near the northern borders of the sea of the period, there are shales and sandstones, and the same is true in the south of England along the southern border of the same sea. This facies of the formation corresponds, in a general way, with the Culm of the continent, and is sometimes known by the same name. The Culm phase of the Carboniferous often contains conglomerates, and locally coal.[1] Beds of marine limestone frequently overlie the Lower Carboniferous coal-seams of Scotland.

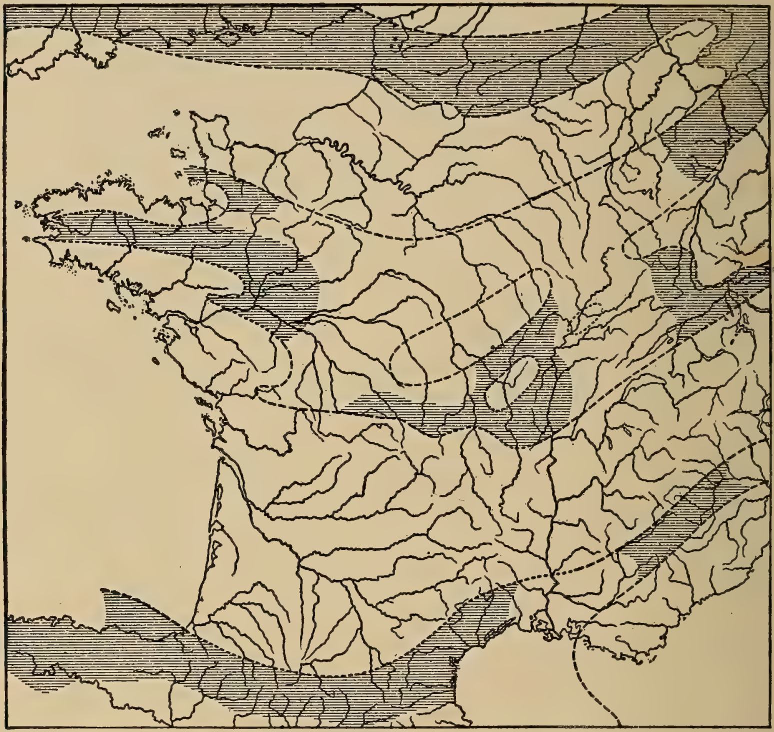

Fig. 234.—Map showing the relations of land and water in France in the early Carboniferous period. (De Lapparent.)

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[1] Geikie, Text-book of Geology, Vol. II, pp. 1045–1051.

The Lower Carboniferous of Silesia, and of central and southern Russia, differs from that in the western part of the continent, in that it is not all marine, and contains much coal. The coal-field of Moscow covers 13,000 square miles, the system resting conformably on the Old Red Sandstone or its equivalent. The coal-beds are mostly thin and poor. The coal-field of Donetz (southern Russia [1]) covers 11,000 square miles, and contains 44 workable beds (some of them Upper Carboniferous) which have an aggregate thickness of 114 feet. Workable coal-beds also occur in the upturned Lower Carboniferous strata on the flanks of the Urals.

The Lower Carboniferous is wanting in most of central France, and eastward through Bohemia,[2] Moravia, and into the region of the Carpathians. Here the Carboniferous proper (corresponding to the American Pennsylvanian) rests on older Paleozoic systems. This tract was probably land during the Early Carboniferous period. In southern Germany the Lower Carboniferous appears in the mountains only.

The Lower Carboniferous of southern Europe is not very different from that of the central part of the continent, a fact which shows that the northern and southern parts of the continent, which constituted such distinct and persistent provinces during the earlier periods of the Paleozoic, were now less sharply defined.

Lower Carboniferous rocks are also found in Spitzbergen, where they rest on the Old Red phase of the Devonian.

Igneous rock.[3]—The Lower Carboniferous system of Scotland and of central Europe is notable for the large amount of volcanic rock which it contains. Volcanic rocks dating from this period, probably largely from its later part, are found at various points in England, Ireland, and Scotland. In Scotland two great types of eruption are recognized: (1) Plateaus, where the volcanic materials from many vents became continuous over areas hundreds of square miles in extent, the lava sometimes having a depth of 1500 feet; and (2) puys, where the ejections were more local, and centered about the vents which discharged them.[4] As the result of the erosion which has taken place, these volcanic rocks have given rise, in Scotland, to considerable belts of hills and table-lands. Some of these volcanic rocks were probably of submarine origin, and some of subaërial origin. Igneous rocks (chiefly granite) dating from the close of the Early Carboniferous are also abundantly associated with the Lower Carboniferous formations of the Harz, Thüringerwald, Vosges, and other mountains of central Europe.

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[1] It is not always easy to distinguish the Lower Carboniferous from the Coal Measures of Russia, from the literature which is available.

[2] Kayser, Geologische Formationskunde, p. 196.

[3] Geikie, Text-book of Geology, Vol. II; also Ancient Volcanoes of Great Britain.

[4] Geikie, Text-book of Geology, 4th Ed.

Thickness.—The thickness of the European Lower Carboniferous is very great, considering the fact that it is so largely of limestone. In England and Ireland, the limestone attains thicknesses ranging up to 2000 feet, and perhaps even to 2500 feet. In the northern part of England and in Scotland, where the beds are clastic, they have a thickness which, at the maximum, is much greater. In Belgium, the limestone is also very thick. These great thicknesses, especially of limestone, bespeak the great duration of the Lower Carboniferous period. 2500 feet of limestone, accumulating at the rate at which limestone is supposed to accumulate, would call for at least some hundreds of thousands, and perhaps millions, of years. The system also has great thickness in Russia.

Close of the Early Carboniferous period in Europe.—The close of the Early Carboniferous period was marked, in Europe, by somewhat wide-spread crustal disturbances. It was at this time that a great system of mountains, sometimes referred to as the Paleozoic Alps,[1] began its development. This system of mountains crossed the central part of Europe, from the islands on the west to the Sudetes mountains, or perhaps beyond, on the east. Their remnants are seen in the Vosges, Black Forest, Harz, Sudetes, etc., mountains of the present time. The development of the Ural mountains appears to have begun at the same time. Geographic changes which were not deformative were also in progress, shifting somewhat the areas of sedimentation. In Europe as in America, therefore, there is a notable break between the Lower and Upper Carboniferous. Unconformity between the two systems is reported along the eastern border of the Schiefergebirge[2] in Saxony, in the eastern Alps, in southern France, and in Spain.[3] These relations, it will be recalled, are in harmony with the phenomena of North America (see p. 507), but the unconformity in Europe appears to be less widespread than in North America.

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[1] Kayser, Geologische Formationskunde.

[2] Kayser, op. cit., p. 170.

[3] Credner, Elemente der Geologie, p. 481.

These unconformities are by no means the only indication of geographic changes at the close of the Lower Carboniferous, for both the distribution of the Carboniferous proper and the character of its formations point to great changes. The Carboniferous rocks are present over considerable areas where the Lower Carboniferous appears never to have been deposited, and they are absent from areas where the earlier system is found. Furthermore, non-marine Upper Carboniferous formations succeed marine Lower Carboniferous, and *vice versa,* over great areas. The succession first named obtains in western Europe, and the second in eastern Europe. Great orogenic movements began in western Europe at the close of the Lower Carboniferous, and continued into the Permian.[1] These changes set off the Lower Carboniferous from the Upper.

Other Continents.—In other continents, where geological work is less advanced, the Lower and Upper Carboniferous have not always been carefully separated. The Lower Carboniferous system appears to be somewhat widely distributed in North Africa, and to be present in the southern part of the continent.[2] Lower Carboniferous formations have been reported in Asia Minor, Persia, in the Kirghiz steppes in Central Asia, in North China and elsewhere. Their faunas are of European types, and the system sometimes carries coal.

In Australia (Queensland and Victoria) and New Zealand, the Lower Carboniferous consists of marine sedimentary beds which are often much disturbed and metamorphosed, and associated with more or less igneous rock. In western Australia the Lower Carboniferous formations (1000 to 1300 feet) contain gypsum and salt.

In South America the Lower Carboniferous is represented in southwestern Argentina by sandstone which contains some coal, and in Chili. In other parts of the continent it has not generally been separated from the Upper Carboniferous.

[1] Kayser, op. cit., pp. 174–5.

[2] Geikie, Text-book of Geol., Vol. II, 4th ed., p. 1056.

CLIMATE.

Most of the data at hand indicate that the climate of the Lower Carboniferous was essentially uniform, and on the whole both genial and moist. The fossil plants and corals of so northerly a land as Spitzbergen, and the relations of the fossils of arctic regions to those of lower latitudes, seem clearly to indicate that climatic conditions were essentially uniform in regions where they are now very diverse.

The data which seem to be in discord with the conclusion that the climate of the period was genial, moist, and measurably uniform are (1) the salt and gypsum deposits of the Mississippian series in Montana, Michigan and Nova Scotia, and the similar deposits in western Australia, all of which suggest aridity, and (2) certain conglomerate formations (the Culm) of western Europe.[1] The latter have been thought to suggest glaciation, but the evidence does not seem to warrant this conclusion. The testimony of the marine fossils continues to indicate rather uniform and genial conditions. This subject will be touched on again, in the more general discussion which follows.

THE LIFE OF THE MISSISSIPPIAN (SUBCARBONIFEROUS).

I. THE MARINE FAUNAS.

Just as there was no profound break in the stratigraphic progress of the American continent at the close of the Devonian, so there was no radical break in the succession of life. The Devonian fauna passed by gradation into the Mississippian. It will be recalled that the life history of the Devonian in North America consisted of a series of great invasions from different quarters, and that the invaders and the invaded mingled with one another until at the close there was a notable approach to a single continental fauna. This change, however, was not complete. The life of the Great Basin was still largely isolated, and there were dependencies of the main fauna that still retained provincial features.

During the opening stages of the Mississippian period there was a continuation of the movement from provincialism toward cosmopolitanism. The fauna of the first epoch in the interior basin, the Kinderhook, belongs to the provincial rather than to the cosmopolitan class; for east of the Cincinnati arch there was a rather distinct fauna, the Waverly, and in the Great Basin a fauna that was largely Devonian in type still lingered in measured isolation, taking on slowly a Mississippian aspect. The Kinderhook fauna proper was merely the leading fauna of the interior, occupying the great Mississippian sea, and varying from region to region in response to the different physical conditions already mentioned.

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[1] Kalkowsky, Ueber Geroll-Thonschiefer glacialen Ursprungs im Kulm des Frankenwaldes. Zeitschr. der deutschen geologischen Gesellschaft, 1893, pp. 69–86.

The Kinderhook Fauna.

One of the more important features of the evolution of the Kinderhook fauna was the progress of the fishes, in which sharks were the leaders; but it will be more satisfactory to treat the fishes of the whole period together after the less roving invertebrate faunas of the several epochs are considered.

The resilience of the crinoideans.—The departure of the Kinderhook fauna from the parent Devonian fauna is shown markedly in the evolution of the crinoids, although, except locally, fossils of these animals are of rare occurrence. They had a very scant development usually throughout the Devonian, and were, in general, quite subordinate to the corals; but in the Mississippian period the relative importance of these groups was reversed. The crinoids not only forged ahead in numbers, but they took on advanced characters. The beginning of this deployment took place in the Kinderhook, and it reached its climax in the next epoch, the Osage, where it will be more fully noticed. Representative forms are shown in Fig. 235, *e* and *f*. Several genera of blastoids were present, all different from those of the Devonian faunas, but they were not as yet abundant, a fact the more notable because of their remarkable development before the close of the Mississippian period. The echinoids and asteroids were still less abundant, a fact in harmony with their very modest development throughout the whole Paleozoic era.

Transition in the aspect of the brachiopods.—The brachiopods of the Kinderhook fauna possess characteristics transitional between those of Devonian and Mississippian types. Among them, the genus *Productus* was conspicuous (Fig. 235, *o*). The Kinderhook species may be said to be anticipatory of the typical Mississippian types,

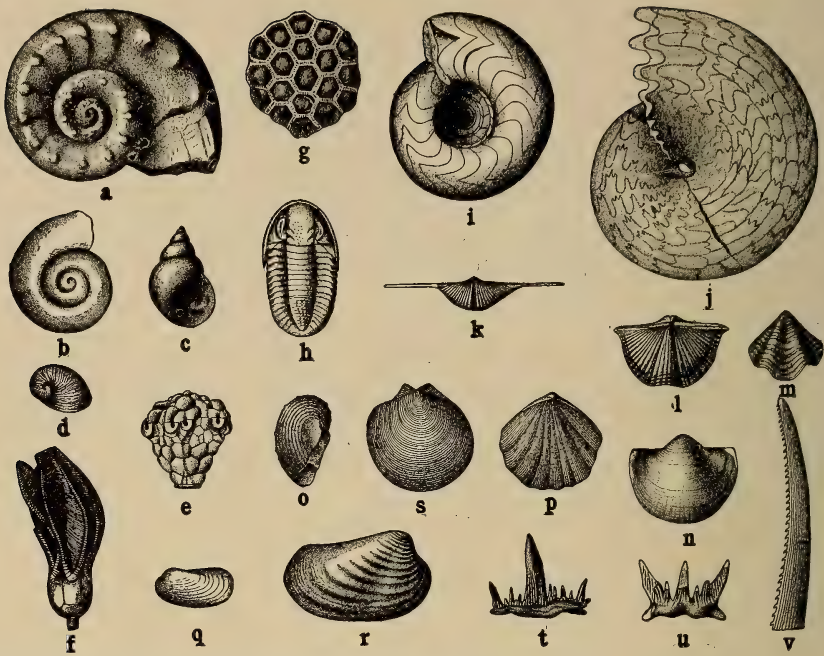

FIG. 235.—THE KINDERHOOK (Lower Mississippian) FAUNA. *Gastropoda: a, Porcellia nodosa* Hall, a shell coiled nearly symmetrically in a plane; *b, Straparollus obtusus* Hall, a low spiral shell; *c, Macrocheilus blairi* (M. and G.), a shell with a moderately elevated spire; *d, Platyostoma broadheadi* S. A. M., one of the capulid shells; all four of these genera are present in the Devonian. *Crinoidea: e, Actinocrinus senectus* M. and G., a camerate crinoid belonging to the family *Actinocrinidæ*, all the members of which are peculiarly Mississippian; *f, Dichocrinus inornatus* W. and Sp., one of the earliest crinoids with only two basal plates. No such type of crinoid base is known anywhere earlier than the Mississippian. With the Devonian, crinoids with four basal plates disappeared, and in the Mississippian, only those with two and three basals are present. *Corals: g, Leptopora placenta* (White), a peculiar compound coral whose relationships are not well understood. *Trilobite: h, Pröetus ellipticus* M. and W. Trilobites are rare in the Kinderhook and the one here illustrated is a good example of their lack of ornamentation. *Cephalopoda: i, Muensteroceras oweni* (Hall), one of the abundant species in the famous Kinderhook goniatite bed at Rockford, Ind.; *j, Prodromites gorbyi* (S. A. M.). This genus has a wide geographic distribution in the Kinderhook, and is the earliest form to show secondary lobing of the sutures. *Brachiopoda: k, Spirifer biplicatus* Hall, a member of the genus retaining a greatly elongate hinge-line, a character which was pronounced among Devonian members of the genus, but not among Mississippian species; *l, Spirifer marionensis* Shum., a species related to such species as *S. disjunctus* of the Devonian (see Fig. 212, p. 476) in its plicated fold and sinus, but it shows an advance in the bifurcating plications upon the sides of the shell; *m, Cyrtina acutirostris* (Shum.), a species of a Devonian genus, no members of which persist beyond the lower Mississippian; *n, Productella pyxidata* Hall, a representative of a genus which had its great development in the later Devonian, only a few forms being present in the Mississippian; *o, Productus arcuatus* Hall; the genus *Productus* is an outgrowth from the earlier *Productella*, and is peculiarly characteristic of the Mississippian, Carboniferous, and Permian faunas; *p, Paraphorhynchus striatocostatus* (M. and W.). A striated rhynchonelloid shell characteristic of the lower Kinderhook horizons of Iowa, northern Missouri and

[*Continued on bottom of p. 521*]

but at the same time they retained many Devonian features. Not a few Devonian species may be named as the probable direct ancestors of Kinderhook species, as, for example, *Cyrtina hamiltonensis*, as the parent of *C. acutirostris* (Fig. 235, *m*); *Spirifer disjunctus*, of *S. marionensis* (Fig. 235, *l*); *Athyris spiriferoides*, of *A. hannibalensis*. A few species believed to be identical with Devonian forms were also present; indeed the Devonian resemblances (see Fig. 235, *k*) are so strong that the earlier paleontologists referred the Kinderhook to the Devonian, classing it with the Chemung.

Other features.—The molluscan contingent was prominent in the Kinderhook faunas. The pelecypods alone have a larger number of species than either the echinoderms or brachiopods. They are especially abundant in some of the arenaceous beds (Fig. 235, *q*, *r*, and *s*). Among them are species indistinguishable from those of the Waverly fauna that inhabited the gulf east of the Cincinnati island. The gastropods were less abundant, but among them the capulids, a group that was conspicuous among the gastropods of most Devonian epochs were the most common (Fig. 235, *a*, *b*, *c*, and *d*). The chief representatives of the cephalopods were the goniatites (Fig. 235, *i* and *j*), and although they are generally rare, they show, in the genus *Prodromites*, a notable advance over any of their known Devonian ancestors, in the more highly complicated lobing of the suture. Trilobites were few and small (Fig. 235, *h*). Their high stage of ornamentation had passed, the day of their final disappearance was drawing near, and they assumed a sober and subdued aspect. The corals (Fig. 235, *g*), though less abundant than in the preceding epochs, were represented by a considerable number of forms, among which the cup-shaped type was most common.

Though without striking characteristics, the fauna represented a notable stage in the evolution of distinctive Mississippian features. It was essentially indigenous, and may be regarded as a transition stage from the late Devonian to the typical Mississippian fauna represented in the following epochs.

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northern Illinois. *Pelecypoda: q*, *Macrodon missouriensis* (M. and G.); and *r*, *Grammysia hannibalensis* (Shum.), both of which have close Devonian relationships; *s*, *Pernopecten cooperensis* (Shum.), a species very characteristic of certain of the higher horizons in the Kinderhook. *Vertebrata: t*, Tooth of *Cladodus springeri* St. J. and W.; and *u*, Tooth of *Pristicladodus springeri*, St. J. and W., the sharp cutting teeth of sharks; *v*, spine of *Acondylacanthus gracilis* St. J. and W.

The Osage Fauna.

The physical conditions of the Osage epoch present the key to the character of its fauna. Its extended shallow sea, relatively free from silt, afforded a rich and expansive field for the climacteric evolution of the varied assemblage of forms that had come together in the preceding epochs under less favorable conditions. There is evidence also of rather free migratory communication with the Eurasian continent by one of the northerly routes, since many species, or closely allied species, were common to the faunas of America and Europe. Between an expanding field for home development, and fair facilities for immigration and emigration, the conditions were ripe for notable evolution. In the main it was an indigenous evolution, but the migratory factor gave it a pronounced cosmopolitan aspect.

The climax of the crinoids.—No single group so well characterizes the fauna and expresses its dependence on physical conditions as the crinoids, whose abundance and diversity were pronounced (Fig. 236, *a–i*). The great order of camerate or "box" crinoids (*Camerata*) now reached the climax of its career. This was the second climax in the career of these crinoids, and perhaps the greatest. Their curve is shown in Fig. 237, in which the curve of the camerate genera is superposed on the composite genera curve, to show the special evolution of the camerates. The rapid decline of the crinoids, almost to extinction, after this climax, as shown by the curve at the right, is one of the most remarkable incidents in the life history of the invertebrates, and, in view of their interesting and beautiful forms, one to be regretted. But in the day of their glory their fecundity was remarkable, as suggested by the fact that a single genus (*Batocrinus*) deployed into more than a hundred species (Fig. 236, *d*). Certain genera, especially *Platycrinus* (Fig. 236, *f* and *g*), *Actinocrinus*, and *Dorycrinus*, were distinguished for their curiously diversified and ornamented forms. The ornamentation of the crinoids at this time reached some such remarkable degree as was attained by the trilobites just previous to their final decadence, and seems to have much the same suggestiveness as to the relations of climax, ornamentation, and downfall, a relationship that singularly enough obtains in human history. Whether the decline and downfall in the two cases were from similar or different causes we cannot here inquire. The ornamentation of the crinoids is observable in all of the more prominent families, and seems to be a clear case of parallel evolution. The ornamentation was effected by the development of surface ridgings, nodes, spines, and other outgrowths from the plates.[1] It is even possible to recognize a distinct advance in the ornamentation during the progress of the epoch. In the earlier (Burlington) stage the crinoids were usually smaller and more delicately ornamented than in the later (Keokuk) stage, when they attained larger sizes, assumed broader features, and took on more extravagant ornamentation. The meaning of all this is not clear, but the repetition of this singular phenomenon at different times, and in quite different groups of organisms, is worthy of notice and thought.

The crinoids made large contributions to the limestones, the characteristic deposit of the epoch, the "encrinital limestone" taking its name from the numerous plates and stems which make up much of its substance.

The distant kin of the crinoids were not equally affected by the conditions of the epoch, although the blastoids were represented by a greater variety of forms than at any other period in their history. The starfishes, though present, did not appreciably depart from the slow development that had been their habit for ages, and much the same is to be said of the brittle stars that were even less common. The echinoids showed a slightly greater movement, and left a record of about a score of species.

The scantiness of the corals.—It is a matter of surprise that the corals had so small a place in this fauna, in view of the general physical conditions which were apparently favorable, though there may have been depths or temperatures uncongenial to them (Fig. 236, *u*). Crinoids are less narrowly circumscribed in these respects than corals. It is more likely, however, that the explanation lies in organic conditions, perhaps in the state of the corals themselves, perhaps in unrecorded enemies, parasitic or otherwise, or perhaps in the pre-occupation and rivalry of the crinoids.

Other features.—The brachiopods, as usual, held a leading place

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[1] Admirable illustrations may be found in the Monograph of Wachsmuth and Springer on "North American Crinoidea Camerata," Mem. Mus. Comp. Zool., Vols. 20–21, and also in the state reports of Iowa, Illinois, and Ohio, especially Geol. Surv. Ill. Vol. 5.

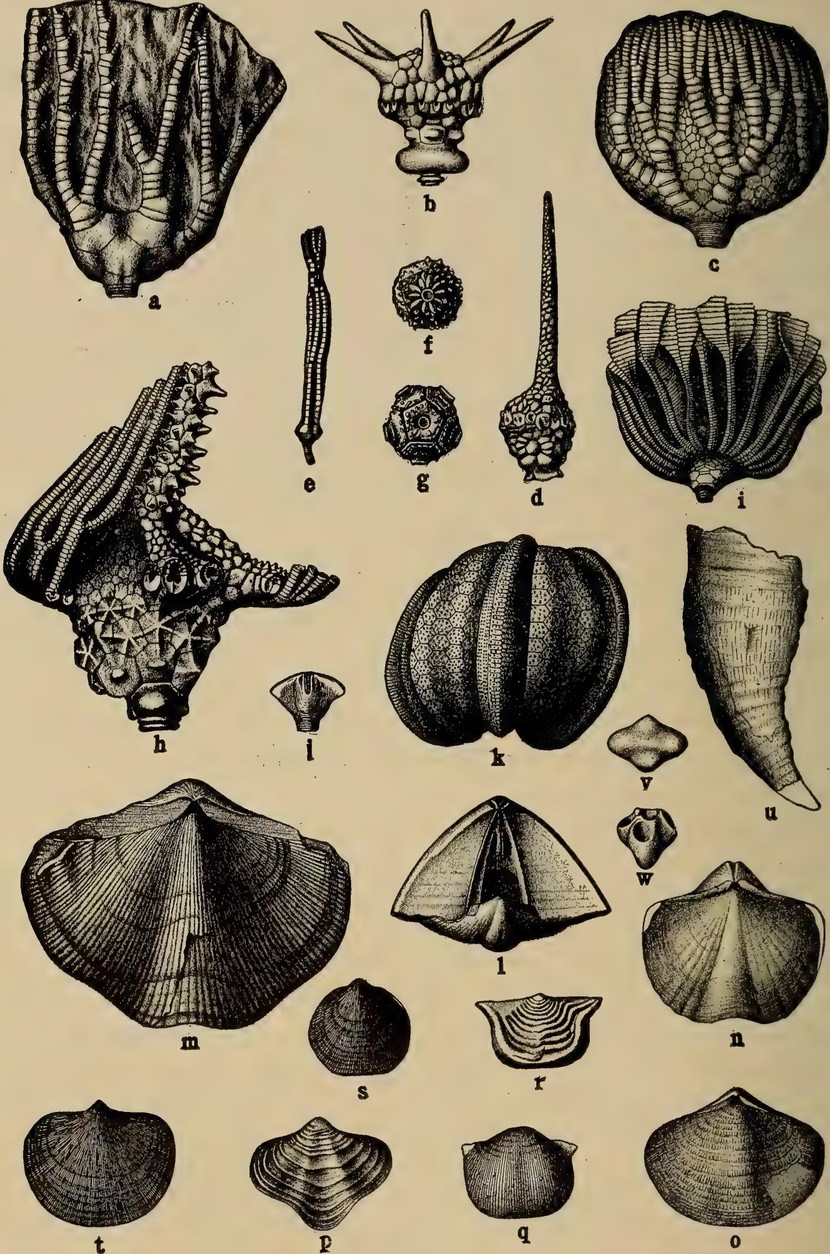

Fig. 236.—The Osage (Middle Mississippian) Fauna. (See opposite page for explanation of figure.)

in the fauna, and some of their species had a wide geographic range, extending to the eastern continents. Some of the typical forms are illustrated in Fig. 236, *l–t*. The molluscan factor was subordinate. A few winged pelecypods, a few capulid gastropods, an occasional pteropod, and an even rarer cephalopod, make up the poor representation of this class. The low estate of the cephalopods, so prominent earlier, and to be so again later, is very notable. They were represented chiefly by the *Nautilus* family.

There were a few lingering trilobites and some other crustaceans, a quite ample growth of bryozoans of much interest, some supposed sponges (Fig. 236, *v* and *w*), and doubtless the less easily fossilized

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Explanation of Fig. 236.—*Crinoidea: a, Barycrinus hoveyi* Hall, one of the fistulate, inadunate crinoids, note the persistence of the uniserial arm structure; *b, Dorycrinus missouriensis* (Shum.), a camerate crinoid of the family Batocrinidæ; note the peculiar development of the basal plates and the spinose plates of the vault; *c, Forbesiocrinus wortheni* Hall, one of the flexible crinoids; *d, Lobocrinus longirostris* (Hall), one of the Batocrinidæ, showing the extravagant development of the anal tube; the arms are removed; *e, Synbathocrinus wortheni* Hall, one of the larviform inadunate crinoids; note the small cup and the simple, uniserial arms; *f, Platycrinus verrucosus* White, and *g, Platycrinus gorbyi* S. A. M.; *Platycrinus* is one of the conspicuous Osage genera; these two figures show different types of ornamentation; *h, Actinocrinus lobatus* Hall; note the high degree of ornamentation of the plates; *i, Eretmocrinus remibrachiatus* (Hall), a representative of a genus of the *Batocrinidæ* characterized by the peculiar spatulate arms. *Blastoidea: j, Orophocrinus stelliformis* (O. and S.), one of the lower Osage blastoids. *Echinoidea: k, Oligoporus mutatus* Keyes. All of the *Palæechinoidea* to which sub-class all Mississippian and Carboniferous sea urchins belong, have more than two rows of plates in each ambulacral and interambulacral area. *Brachiopoda: l, Syringothyris subcuspidatus* (Hall); the genus of which this is a representative is an offshoot from Spirifer, characteristic of the Mississippian faunas; it is characterized by its high area, punctate shell structure, and a peculiar tube between the dental plates; *m, Spirifer logani* Hall, the American representative of the *Spirifer striatus* of the European Mountain Limestone fauna; note the large size, the completely plicated shell, with the plications bifurcating on both the fold and on the sides of the shell. The surface is marked by very fine striæ not shown in the figure; *n, Spirifer suborbicularis* Hall, another type of spirifer, closely allied species of which occur in America and Europe; *o, Reticularia pseudolineata* (Hall), one of the spire-bearing brachiopods having a closely allied species in the European Mountain Limestone fauna; *p, Athyris lamellosa* L'Eveille, a species which occurs both in America and in Europe; *q, Productus burlingtonensis* Hall, one of the species of this peculiarly Mississippian, Carboniferous and Permian genus, which occurs abundantly in the lower Osage; *r, Leptæna rhomboidalis* Wilck, a species which has persisted from Ordovician times, and which appears for the last time in the Osage fauna; *s, Rhipidomella burlingtonensis* (Hall), and *t, Schizophoria swallovi* Hall, two species which are among the last representatives of the orthids, a family whose great development was in the Ordovician; both species have near relatives in the European Mountain Limestone faunas. *Coral: u, Zaphrentis centralis* E. and H., the most characteristic coral of the Osage faunas. *Sponge: v–w, Palæacis obtusum* M. and W. The exact nature of this fossil is not well understood. It is usually placed with the sponges, although by some it is included with the corals. (Weller.)

forms necessary to make up a self-sustaining assemblage. There

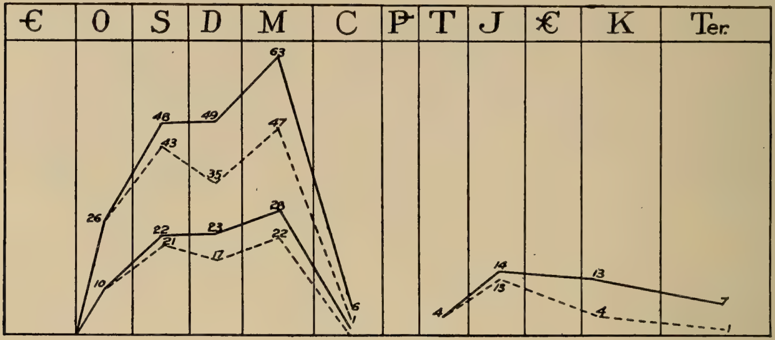

Fig. 237.—The two upper curves in this diagram, shown in the Paleozoic periods, and their continuation in the Mesozoic, constitute the evolution curve of the entire class, Crinoidea. The two lower curves in the Paleozoic periods represent the evolution curve of the order Camerata of the class Crinoidea, the order becoming extinct just before the close of the Paleozoic. The discontinuity of the lines across the Permian column, *P*, represents the imperfection of our knowledge of the Permian faunas, and not that the crinoids became extinct in the Pennsylvanian, *C*, to reappear in the Trias. In all the curves, the dotted line represents the number of new genera initiated, and the full line the total number of genera present, the difference between the two representing the number of genera which passed over from the preceding period. The data for the curves have been compiled from the publications of Wachsmuth and Springer.

was beyond doubt an ample marine flora, but it made only a feeble, obscure record.

The Waverly Fauna.

Contemporaneous with the evolution of life in the successive Kinderhook and Osage seas, there was a rather more provincial development in the gulf east of the Cincinnati axis. There was no definite barrier between the gulf and the sea on the west, but, owing partly to the partial separation and more perhaps to the physical conditions, the fauna in the Waverly gulf was sufficiently distinct to warrant separate recognition.

The Waverly fauna was characterized negatively by the rarity of both corals and crinoids, the apparent reason being their dependence on clear seas. To this there was one notable exception. At Richfield, Ohio, there flourished a crinoid field occupied by the species of several genera. These genera were also represented in the Osage sea to the west, but the species there were wholly different. Apparently a colony of their common ancestors had established itself at this locality, perhaps in late Devonian times, and, finding it free from the hostile conditions prevalent in the region, flourished in isolation for a period sufficiently long to differentiate species of its own, after which it died out.

As might be anticipated from the silty conditions, the pelecypods were the most prominent feature of the fauna. Many of them were of the same species as the previous occupants of the region in the closing Devonian times, showing again the close relations of the two periods. The other mollusks were relatively less abundant. Brachiopods were numerous and resembled those of the contemporaneous Kinderhook and Osage faunas; but they were, on the whole, rather less differentiated from the ancestral Devonian forms, doubtless because the change in their environment had been less notable. The other forms were not very different from those of the more open sea to the westward.

The Waverly fauna was the direct descendant of the Devonian faunas that had occupied the same ground and had changed but slowly, as the environment remained nearly constant. It was modified by some immigration of the Kinderhook and Osage types, and this, combined with its own conservative progress, caused it to take on gradually a Mississippian aspect, while it retained many Devonian characteristics. It is a good illustration of a lingering fauna where the conditions are conservative, though not so good an illustration as the next fauna.

The Great Basin Fauna.

It will be recalled that in Devonian times the Great Basin was a province by itself, in which a slow faunal development of provincial aspect, only slightly modified by foreign contributions, took place. At the horizon rather arbitrarily fixed upon as the upper limit of the Devonian system, there appears to have been no faunal break. It is necessary to speak with some reservation, for the region has not yet been thoroughly worked, paleontologically. The transition to the Mississippian facies seems to have taken place very gradually, through the progressive evolution of some forms, the elimination of others, and the immigration of a few from westerly sources, but, until after the Osage epoch, rarely from easterly sources, so far as now known.

This distinctive phase of the Great Basin fauna was contemporaneous with the Kinderhook and Osage faunas of the interior sea, and at the close of the Osage epoch it united with the latter to form the Genevieve (St. Louis-Kaskaskian) fauna.

Previous to this union, one of the most salient distinctions between the Great Basin fauna and the Osage fauna was the rarity of crinoids in the former. Although the Osage sea stretched westward to the foot of the ancestral Rocky Mountains, and was prolific in crinoids, they do not seem to have invaded the Great Basin sea, one of the facts which point to the distinctness of the two provinces. Brachiopods were abundant in both provinces, but the species were different. The large spirifers of the type of *Spirifer striatus* (compare Fig. 236, *m*), so characteristic of the Osage fauna and of the "mountain limestone" of Europe, as well as other typical forms, were absent. On the other hand, there had arisen, under the genus *Productus*, probably by parallel evolution, species closely allied to some found in the Osage fauna, implying that the Great Basin fauna was taking part, in a conservative way, in the Mississippian progress. Were it not for such forms of Mississippian aspect, and the evidence that developed when the two faunas commingled, the Great Basin fauna might be thought to be Devonian, for there remained many species of marked Devonian aspect. Among these was *Leiorhynchus quadricostatus*, known at the east only in Hamilton beds, but in the Great Basin found to commingle in the upper horizons with Mississippian types. *Productella*, a Devonian type, was still living in the Great Basin, although it had disappeared from the interior after the Kinderhook epoch (Fig. 235, *n*). Numerous other species of Devonian aspect were associated with forms of Mississippian aspect.

Judging from present knowledge, the pelecypods were even more abundant than the brachiopods, another point of contrast with the Osage fauna. The pelecypod species seem to have been peculiar to the Great Basin sea, and doubtless originated there, and later became extinct without migration. There were also many gastropods, among which were air-breathers (*Physa prisca* and *Zaptychius carbonaria*), the oldest aquatic pulmonates known. Terrestrial pulmonates, theoretically evolved from aquatic pulmonates, have, however, been described from Devonian strata. Cephalopods were not abundant, and no goniatites have thus far been found among them. Trilobites were about as rare as in the eastern fauna, and of the same genera. Corals were present in some abundance, the horn-shaped type predominating. No bryozoans have been reported, nor have any fishes been described. Unless this be due to the imperfection of the record, or of present investigation, it adds much to the evidence of the distinctness of the province, for fish abounded in the eastern sea, and they are free-moving forms of migratory habits.

As remarked in the physical discussion, the barrier which enforced the distinctness of the Great Basin and the Kinderhook-Osage seas appears to have been an elongated insular tract lying about where the Rocky Mountains (not then elevated) now stand. The yielding of this barrier about the close of the Osage epoch, by erosion or submergence, permitted this singular semi-Devonian, semi-Mississippian fauna to invade the greater eastern sea, and, commingling and combating with the Osage fauna, to initiate a new fauna, the Genevieve, the closing fauna of the Mississippian period in the interior. It flourished while the St. Louis and Kaskaskia formations were being deposited.

The Genevieve (St. Louis-Kaskaskia) Fauna.

As remarked in the physical discussion, the St. Louis formation marks the stage of maximum sea-extension in the interior of North America, and the Kaskaskia deposits the inauguration of a restrictive movement. The Genevieve fauna, representing the two stages, may be regarded as the culmination of the cosmopolitan evolution of the Mississippian life on the North American continent, and the initiation of its decline. The commingling of the Great Basin and the Osage faunas was the most declared feature. It introduced into the main Mississippian sea what seemed to be a retrograde feature, although it was a part of the progressive movement toward a more cosmopolitan fauna. Species of a Devonian aspect that had lived along conservatively in the isolated Great Basin province, migrated eastward, and were found among species whose evolution had reached an advanced Mississippian phase. The faunal average seemed to be set backwards. Among these were several productellas, and *Leiorhynchus quadricostatus*, previously mentioned as lingering Devonian forms in the Great Basin fauna. That these really came from the west seems to be confirmed by the presence with them, as far east as Arkansas, of *Rhynchonella eurekensis*, a peculiar and distinctive Nevada species.[1]

The decline of the crinoids.—Either the invaders, or else changes in the physical or organic conditions, influenced adversely the crinoids, for, although they still formed a large factor in the assemblage, they had fallen off much from their abundance in the Osage fauna, and had undergone notable changes of form (Fig. 238, *a–c*). Less than 25 species of camerate crinoids are known in the entire Genevieve fauna, as compared with upwards of 300 in the Osage. Among these no Osage species persisted, and in the faunas younger than those of the St. Louis limestone, not even an Osage genus. The inadunate and flexible crinoids, however, did not show so remarkable a decline. Among the crinoids some new and curious forms were developed, among which may be mentioned *Agassizocrinus* (Fig. 238, *a*), *Pterotocrinus* (Fig. 238, *c*), and *Acrocrinus* (Fig. 238, *b*).

The culmination of the blastoids.—The blastoids had their climax here so far as numbers of individuals are concerned, although there was much greater generic diversity in the Osage faunas. The leading genus, *Pentremites* (Fig. 238, *d*), was so prolific in individuals in some beds as to give rise to the name Pentremital limestone. A swift decline seems to have followed this sudden climax, and the beautiful forms disappeared for reasons quite unknown.

The last of the known cystids, a species of the peculiar, horizontally flattened, disk-like *Agelacrinidæ*, a family which had persisted from the Ordovician period, was a member of this fauna.

Echinoids were present, among them an ample rotund form suggestively named *Melonites*, and resembling the *Oligoporus* (Fig. 236, *k*) of the Osage epoch. Although the echinoids had appeared much earlier, it was in the Osage and Genevieve faunas that they for the first time showed signs of the prominent development they were to attain later.

Partial recovery of the corals.—The corals seem to have profited by the decline of their rivals, the crinoids, or by other conditions, for they were more numerous than in the Osage fauna. A compound coral, growing to great size, *Lithostrotion canadense,* became conspicuous in the St. Louis limestone at some localities. Aside from this, however, the simple horn-shaped forms remained the most common.

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[1] Williams: Am. Jour. Sci., Vol. XLIX, p. 94.

New devices of the bryozoans.—The reticulate bryozoans made a new departure in their mode of support. The delicate branches of their colonies cannot extend themselves indefinitely without special means of support. As one mode of securing this support, the genus *Lyropora* secreted a U-shaped calcareous base, upon the inner concave surface of which the rest of the colony spread itself. As another and more successful mode, the genus *Archimedes* (Fig. 238, *q*), which made its first appearance in the Osage, secreted an axis with a spiral flange upon which the colony spread itself, producing a unique form whose slight resemblance to Archimedes' screw has given it name. The *Archimedes* became so abundant in the Kaskaskia epoch that some beds of the Kaskaskia formations are known as the Archimedes limestone, on account of the great abundance of the axes of this genus.

The protozoans make a record.—For the first time there is clear evidence that the protozoans were an important factor in the fauna. It is not to be understood that they were not really a vital element before, for theoretically there is good reason to believe that they had long been abundant; but they now record themselves in a so-called oölitic limestone in the St. Louis formation, certain layers of which are almost wholly composed of a foraminiferal shell, *Endothyra baileyi* (Fig. 238, *x* and *y*). On account of their globular form, the shells of this genus have been mistaken for oölitic concretions, and have given a misleading name to the formation.

Changes in the brachiopods.—A notable modification in the aspect of the brachiopods took place (Fig. 238, *g–p*). The large spirifers of the *striatus* type disappeared, though some small spirifers remained (Fig. 238, *j*), while *Productus* (Fig. 238, *g* and *h*) continued to be very abundant and characteristic. *Seminula* (Fig. 238, *l*), *Eumetria* (Fig. 238, *m*), and *Spiriferina* (Fig. 238, *k*) were well represented. An odd feature was the diminutive size of the brachiopods, as well as of all other forms, in the Spergen Hill fauna of the Bedford limestone of Indiana, although they were remarkably abundant. The associated fossils of other kinds were also diminutive, implying general pauperizing conditions of some sort, for the species seem to be identical with those that grew larger elsewhere. It is not improbable that this limestone was deposited in a partially isolated body of water that was so highly charged with lime and other salts as to be somewhat unfavorable to life. A similar diminutive fauna is recorded from Idaho.

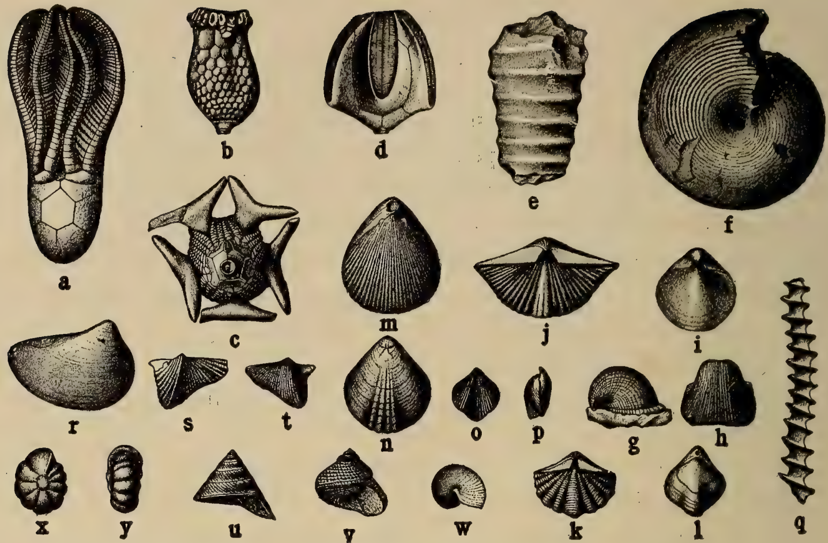

FIG. 238.—THE GENEVIEVE (UPPER MISSISSIPPIAN) FAUNA. *Crinoidea: a, Agassizocrinus dactyliformis* Shum., one of the inadunate crinoids which has lost its stem and become a free swimming creature, at least in its adult condition; *b, Acrocrinus amphora,* W. and Sp., a peculiarly specialized camerate crinoid with a large number of supplementary plates introduced between the basal and radials. It has but two basal plates, not shown in the figure. This genus occurs in the Genevieve and in the Carboniferous, being the only genus of camerate crinoids crossing this line; *c, Pterotocrinus bifurcatus* Weth. This genus is restricted to the Genevieve faunas. It is a camerate crinoid with two basals, and possesses five remarkable spines developed from the ventral surface and produced beyond the arms. *Blastoidea: d, Pentremites robustus* Lyon. Many species of this genus are known in the Genevieve faunas, some species being represented by innumerable individuals. *Cephalopoda: e, Orthoceras annulato-costatum* M. and W., one of the more ancient straight cephalopods, occasional species of which persisted to the close of the Paleozoic; *f, Goniatites kentuckiensis* S. A. M., a notable feature of the Genevieve faunas is the recurrence of the goniatites after their absence from the Osage faunas. *Brachiopoda: g, Productus marginicinctus* Prout, and *h, Productus fasciculatus* McCh., two of the numerous species of this genus which constitutes a conspicuous element in the Genevieve fauna; *i, Martinia glabra* M. and W., one of the brachiopods having much closer relatives in the Devonian than in the Osage faunas; *j, Spirifer increbescens* Hall, one of the most characteristic species of the later Genevieve faunas; *k, Spiriferina spinosa* (N. and P.), a representative of a genus which was an outgrowth from Spirifer, and has its greatest development in the Genevieve and Carboniferous faunas. It is characterized by its punctate shell structure; *l, Seminula subquadrata* (Hall), a species which has no near ally in the earlier faunas, but is closely related to later Carboniferous species; *m, Eumetria marcyi* (Shum.), a representative of a genus which is abundant in the Genevieve faunas and which was also present in the Kinderhook, but absent from the Osage faunas until near the close of that epoch; *n, Leiorhynchus quadricostatum* (Van.), a species common in some portions of the eastern Hamilton faunas, but absent from the Mississippian sea during later Devonian, Kinderhook, and Osage time It persisted in the Great Basin region and reappeared in the interior near Batesville, Arkansas, in a limestone of the age of the St. Louis limestone; *o* and *p, Rhynchonella eurekensis* Walc., a peculiar Great Basin species which occurs with *Leiorhynchus quadricostatum* near Batesville, Arkansas. *Bryozoa: q, Archimedes*

[*Continued on bottom of p. 533.*]

The Mollusks.—The pelecypods (Fig. 238, *r–t*) were rather abundant, and in some of the sandy and silty beds were the predominant forms. Some of them still retained a Devonian aspect, and those in the Indiana foraminiferal (Bedford) limestone were diminutive, like the brachiopods of that formation. The gastropods (Fig. 238, *u–w*) were more diversified than in the Osage fauna, and some Devonian genera which had apparently been absent from the Osage reappeared. The cephalopods (Fig. 238, *e* and *f*) also became more abundant than they had been in the Osage. The goniatites reappear in several species. Possibly these and some of the other mollusks of Devonian aspect which reappeared in the territory from which they had been absent during the Osage epoch came in from the Waverly gulf on the east, and not from the Great Basin sea from which the Devonian forms previously mentioned quite certainly came. Both of the relatively isolated bodies of water appear to have fostered a less rapid evolution than the more open sea between them with its foreign connections and cosmopolitan relations. This accords with a general principle in history.

Other forms.—Trilobites were almost unknown, and the other crustaceans left an unimportant record. The sharks and other fish were important and will be considered presently.

The most striking peculiarity of the fauna, it may be repeated, resulted from the invasion of the more conservative fauna of Devonian aspect from the Great Basin sea, and perhaps from a similar incursion of lingering forms from the Waverly gulf on the east. The remarkable thing is that these should have succeeded, so far as they did, in impressing themselves on the composite result, and in giving tone to the whole. It is more natural to expect an antiquated fauna to be overwhelmed by a younger and more progressive one. It would be interesting to know what happened from the counter-migration

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swallovanus (Hall), one of the peculiar screw-like axes for the support of the colony in this genus. *Pelecypoda: r, Schizodus chesterensis* M. and W.; *s, Conocardium prattenanum* Hall; and *t, Conocardium meekanum* Hall, three species of Genevieve pelecypods which have closer relatives in the Kinderhook and Devonian faunas than in the Osage. *Gastropoda: u, Eotrochus concavus* Hall, *v, Pleurotomaria nodulostriata* Hall, and *w, Bellerophon sublaevis* Hall; three gastropods, all from the diminutive Spergen Hill fauna; all of them have nearer relatives in the pre-Osage than in the Osage, and related forms again occur in the Carboniferous. *Protozoa: x* and *y*. *Endothyra baileyi* Hall, a small foraminifer, much enlarged, which occurs in great numbers in the Bedford limestone of Indiana. it has often been mistaken for oölite grains.

of the Osage fauna into the Great Basin region; but this does not seem to have been worked out. With little doubt the conservative invaders of the interior sea were favored by physical conditions, which appear to have grown progressively more and more like those to which the Devonian types had become adapted, and less and less like those to which the special Osage forms were fitted. There is danger, however, of over-estimating the Devonian facies, because of its interest. The total assemblage bore a pronouncedly Mississippian aspect.

This persistence of Devonian types through to this, the last recognized epoch of the Mississippian period, taken with the close continuity of the life of the last Devonian epoch with that of the first Mississippian epoch, and the absence of any notable physical break at that point, raises the question whether the Mississippian might not better have been regarded as the closing portion of the Devonian period. This would have given to the united period a cosmopolitan climax in the life of the Osage-St. Louis limestones, and a fitting close in the decline of many forms, and the unconformity at the summit of the Mississippian. But no divisions of a history, which is in reality continuous, can be altogether without infelicities. The pulsations of the history, which alone are the true basis of natural divisions, are rarely the same everywhere at the same time, and in all their aspects.

With the close of the Mississippian period, the chief center of life interest passes from the sea to the land, first to the vegetation of the Coal period, and then to the land vertebrates. The history of the marine invertebrates will therefore be followed with less fullness. With the introduction of fishes it had reached its great adjustments, and its further history bears a close likeness to the struggles and adaptations of the history already sketched.

The Evolution of the Fishes in the Mississippian Period.[1]

Many of the ancient invertebrates were as fixed as plants, and their migrations were confined to their early stages; but, quite in contrast, the fishes were constant rovers, and their distribution was relatively free and rapid. While restrained by conditions of food, temperature, etc., they were relatively independent of local conditions, and the minor stages of their progress are less significant than the general ones. They are therefore discussed here for the period as a whole.

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[1] References: Newberry, Worthen and St. John, Ill. Geol. Surv., Vols. II, IV, VI, VII; Newberry, Pal. Ohio, Vols. I and II; Leidy, Trans. Am. Phil. Soc., Vol. XI; A. S. Woodward, Vert. Pal.; Dean, Fossil Fishes.

Fish appear to have first effectually invaded the open sea in the Devonian period, but during that period true marine fishes seem to have been inferior, in number and variety, to those of the inland waters. But by the middle of the Mississippian period the marine fishes had made such relative progress that they were in unquestioned supremacy, while the fresh-water forms had notably declined, if we may trust the record. The extension of the epicontinental seas, and the consequent reduction of the land-areas, and doubtless the land-waters, favored the former and restricted the latter. In the seas, the supremacy of the sharks was almost uncontested. The cephalopods, probably the master forms among the invertebrates, were no match for the newcomers and, as already noted, played a very small part in the life of the times. The great sea reptiles and sea mammals, which later preyed upon and kept in subjection the sea fishes, had not yet come to dispute their sway. Under these conditions, and in a new, rich, and expanding realm, it is not surprising that the fish of the period had a really wonderful development. They were apparently much more abundant than in any later period; at least this is true of the sharks. Up to 1889, about 400 species, nearly all elasmobranchs, had been reported from the Mississippian formations of America, and about 200 additional species from Europe.[1]

The relics are chiefly teeth, spines, and dermal ossicles, and perhaps the number of species is exaggerated by duplicate naming, though this is doubtless much more than offset by the unrecorded forms. The elasmobranchs held undisputed precedence, and of these at least three-fourths had crushing or pavement teeth, adapted to breaking the shells of mollusks and crustaceans, and the trituration of seaweeds.[2] The tooth-pavement was formed of large plates of thicknesses ranging up to one and one-half inches, composed of solid dentine below and a thick sheet of enamel above, which was pitted, ridged, or otherwise roughened to prevent the slipping of the prey. The multiplication of these chonchivorous sharks introduced a new factor into the invertebrate struggle for existence, and perhaps accounts for the decline or disappearance of some forms and the modification of others.

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[1] Newberry, Pal. Fishes, N. Am. Mon. XVI, U. S. Geol. Surv., 1889, pp. 182–83.

[2] Newberry, ibid., p. 184.

The number of spines preserved is exceptionally great when compared with the teeth and dermal ossicles, which are about equally well adapted to preservation. The proportion is very much greater than that of later periods, including the present, and implies that the sharks bristled with spines to a degree not retained in later times. The loss of spines in later ages, like the loss of the armor-plates and other clumsy defensive devices, may be assigned to replacement by agility, intelligence, and more effective weapons of attack, as Newberry has suggested; but their great development at this time doubtless had its special reason in the fact that most of the sharks were only provided with pavement teeth, which were ineffectual weapons against those sharks that were armed with piercing and cutting teeth, and hence the former had especial need for a bristling array of spines as a defense against their aggressive kin.

Sharks with piercing teeth were represented at the very opening of the period by *Cladoselache*, Fig. 239, and later by *Cladodus* and allied genera which were numerous and wide-spread. Some of these were large and formidable fishes, "armed with teeth in many rows, several hundred in each set." (Fig. 235, *t* and *u*). The petalodonts were a conspicuous group of sharks with peculiar cycloid cutting teeth. The arthrodirans, which were abundant and gigantic during the transition period from the Devonian, lingered in reduced importance through

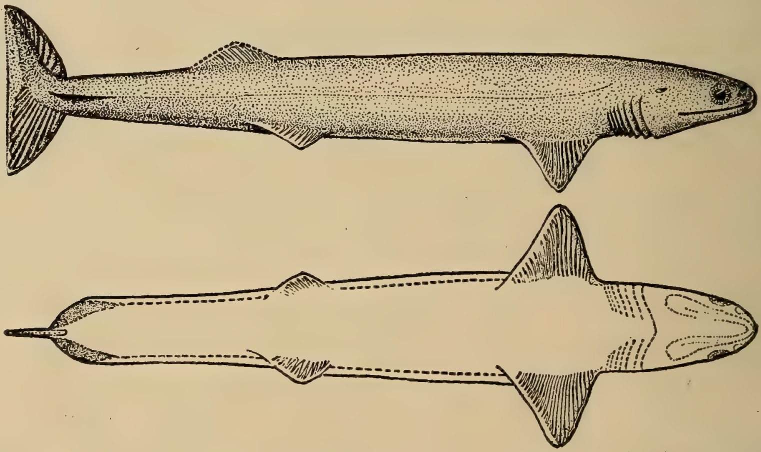

Fig. 239.—*Cladoselache fyleri* Newb. Restoration by Dean about one-fifth natural size. From Cleveland Shales, Ohio. Often referred to the Devonian. (After Dean.)

this period and into the next, when they disappeared. The lung-fishes had declined, but were represented by *Ctenodus*. The holoptychians had disappeared, but the crossopterygians were represented by several genera that took on a closer external resemblance to modern forms.

Of the fishes frequenting the inland and coastal waters, probably the culminating type was now actinopterygian of the order to which the modern garpike belongs. The curious tribe of ostracoderms had nearly or quite disappeared.

The fishes probably made up the whole, or nearly the whole, of the vertebrate fauna of the seas. The ostracoderms may have entered the sea, as they are sometimes reported in marine faunas, but they were probably fresh-water forms in the main. There are reasons for thinking that amphibians frequented the fresh waters and the adjacent lands, but probably not the seas.

II. The Land Life of the Mississippian.

Since the period was one of sea extension and its deposits mainly marine, the record of land life is poor. There was doubtless some notable restriction of the terrestrial life by reason of the encroachment of the sea. So far as may be gathered from the record, the main Devonian lines were perpetuated. Enough fossil vegetation has been recovered to show that all the leading groups of Devonian plants were represented. There were true ferns (*Archæopteris*, *Megalopteris*, *Sphenopteris*, *Pseudopecopteris*, etc.) probably *Cycadofilices* (*Alethopteris*), *Equisetales* (*Calamites*, *Annularia*, *Bornia*, *Astrophyllites*, etc.), *Sphenopyllales* (*Sphenophyllum*), *Lycopodiales* (*Lepidodendron*, *Sigillaria*, *Ulodendron*, *Knorria*, *Halonia*, etc.), gymnosperms (*Cordaïtes*), and the fossil seeds *Cardiocarpus*, *Trigonocarpus*, etc., commonly regarded as the fruit of cordaites.

The most interesting suggestion of advance in land life is found in the footprints of a supposed amphibian named *Peleosauropus* (*Sauropus*) *primævus*, described by Lea from the Mauch Chunk shale near Pottsville, Penn. There are six double imprints, in which the track of the hind foot partially covers that of the front foot. They imply a stride of about thirteen inches, and a breadth between outer toes of eight inches. The trail of a tail an inch wide accompanies the footprints. The slab on which they are impressed is ripple-marked and pitted by rain-drops, implying a freshly emerged mud-flat again covered before the impressions were lost.[1] This solitary record probably stands for many amphibians that had already attained a distinctive development, a suggestion that is supported by the rather wide differentiation which the amphibians presented when first they were well preserved in the next (Coal Measures) period. The European record is better, nearly complete specimens referred to the labyrinthodonts having been found in the Edinburgh (Lower Carboniferous) coal field of Scotland.[2]

Probably the insects and their allies found in the preceding period were represented, but their fossils are not known to have been found.

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[1] Dana's Manual, p. 644.

[2] Described by Huxley, under the name *Pholidogaster*, Vol. XVIII, Q. J. G. S.

CHAPTER X.

THE PENNSYLVANIAN (COAL MEASURES, CARBONIFEROUS PROPER) PERIOD.

Formations and Physical History.

The system of rocks lying upon the Mississippian was formerly known as the Carboniferous proper, and this name is still in common use. The name has its explanation in the fact that this system contains the great coal deposits of the eastern part of North America. The need of a name to distinguish this system of rocks from those which have been described under the name Mississippian has long been felt, and the name Pennsylvanian, which has recently come into wide use in this country, was adopted because the system is well developed and well known in Pennsylvania. The Pennsylvanian system includes the Pottsville conglomerate (Millstone grit) below and the Coal Measures above.

The Pottsville Conglomerate (Millstone Grit).

The lowermost formation of the period in the Appalachian region is generally sandstone or conglomerate (Pottsville conglomerate at the north; Lee conglomerate, Lookout conglomerate, Millstone grit, etc., farther south [see p. 557 *et seq.*]), which betoken shallow water. Over wide areas it is unconformable on the Mississippian system, as already noted. In some places the Pottsville conglomerate appears to be a true basal conglomerate, representing the deposits made by the sea as it transgressed the surface of the recently exposed Mississippian formations. In such places it is sometimes made up partly of the cherts derived from the Mississippian beds, showing that the latter had undergone prolonged decay before the deposition of the conglomerate. In other places the pebbles of which the conglomerate is composed seem not to have been derived from local sources. This likewise argues for wide-spread emergence before the epoch of the Millstone grit, for on a land surface streams may shift materials great distances.

From its coarser conglomerate phases in the east, the Pottsville conglomerate grades westward into sandstone (Mansfield sandstone of Indiana,[1] Parma sandstone of Michigan,[2] Graydon sandstone of Missouri,[3] and Millstone grit[4] of Arkansas), and with local conglomeratic phases the sandstone persists over the interior. At various points in the east the formation contains thin beds of coal (Fig. 242), showing the local beginnings of the conditions which existed later over wide areas,[5] and in the southern Appalachians it is a chief source of coal.[6] The beds of the interior referred to this epoch are thought to represent the later part of the epoch only, while the series in the Appalachian mountains includes beds referable to earlier stages of the epoch as well. In other words, the area of deposition was extended westward as the epoch advanced. Even at the east there is sometimes a great unconformity between the Mississippian and the Pottsville series (see p. 508).

The formation varies in thickness from 1200 feet in the South Anthracite basin of Pennsylvania, to as little as 65 feet in some parts of western Pennsylvania. The unequal thicknesses are due partly to the unevenness of the eroded surface on which it rests, partly to unequal rates of sedimentation, partly to unequal duration of the time of sedimentation in different regions, and partly perhaps to inclined deposition, thinning off shore. Half of the formation in eastern Pennsylvania is thought to have been deposited before deposition began in the western part of the state.[7] The formation has a thickness of about 500 feet in Maryland[8] and of 200 to 1500 feet in West Virginia.[9] Further details as to thickness are given on pp. 557–663.

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[1] 22d, 26th, and 27th Ann. Repts., Dept. of Geol., etc.

[2] Lane, Geol. Surv. of Mich., especially Vol. VII.

[3] Geol. Surv. of Missouri, Vol. XII, and 22d Ann. Rept., U. S. Geol. Surv., Pt. 2, p. 88.

[4] Geol. Surv. of Arkansas, Vol. V, 1892.

[5] White (I. C.), West Virginia Geol. Surv., Vol. II.

[6] Hayes, 22d Ann. Rept., U. S. Geol. Surv., Pt. III, p. 235.

[7] White (D.), 20th Ann. Rept., U. S. Geol. Surv., Pt. II, pp. 755–918, and Brownsville-Connellsville folio, U. S. Geol. Surv., p. 8.

[8] Prosser, Jour. Geol., Vol. IX, p. 422. Also Martin, Maryland Geol. Surv., Report on Garrett Co., pp. 100–110.

[9] White, West Virginia Geol. Surv., Vol. I, p. 211.

The formation is usually so firmly indurated that where it has been tilted its outcropping edge develops ridges.

The Millstone grit, usually a coarse, conglomeratic red sandstone, occurs in Nova Scotia, where it contains occasional lenses of coal and shale.

In the western part of America, the Millstone grit formation has not been recognized. While deposits representing the epoch probably occur, they have not commonly been differentiated from the beds below and above. Locally, however, there are conglomeratic beds which may prove to be the time-equivalent of the Millstone grit of the east. If the Carboniferous (corresponding to Pennsylvanian) of the west is not more generally unconformable on the Lower Carboniferous than present data indicate, the two systems here afford another illustration of the general fact that different regions on the same continent do not always undergo the same changes, or receive similar deposits at the same time. So true is this, that a shallow-water formation, like the Pottsville conglomerate, in the eastern part of the continent, would afford no sufficient warrant for supposing a like formation to have been made in the western. The deposits of the Pennsylvanian (Carboniferous) period in the eastern and western parts of the continent also show that a classification which fits one region may have little applicability to another, so far as details are concerned.

THE COAL MEASURES.

Above the Pottsville conglomerate and its equivalents in the central and eastern parts of the continent lie the formations known collectively as the Coal Measures, a series of beds somewhat unlike any heretofore considered. They consist of a great succession of alternating beds of shale, sandstone, conglomerate, limestone, coal, and iron ore. While the succession differs greatly in different regions, shale and sandstone perhaps recur more frequently than any other members of the series, and in thicker beds. Limestone has a more limited development, and conglomerate is relatively unimportant. The coal and some of the iron ore are in layers interstratified with the clastic beds, and are to be looked upon as strata of rock, the same as the associated sandstones and shale. Important as the coal and iron ore are from an economic point of view, they make up but a small part of the system. Although there are many beds of coal in some regions, and although some of them have great thickness (40 to 50 feet) the proportion of coal in the Coal Measures is rarely one foot in forty, and the proportion of iron ore is much less.

The Coal Measures are differently divided in different regions. A twofold division, namely a Lower and an Upper, is common. To these series, local names are often applied. In Iowa, for example, the Lower division is designated *Des Moines*, and the Upper, *Missourian.*[1] In other regions, as in Ohio, a fourfold division has been made as follows: (1) Lower Coal Measures; (2) Lower Barren Measures; (3) Upper Coal Measures, and (4) Upper Barren Measures. The last is now generally referred to the Permian period. More recently the following classification of the Pennsylvanian and Permian systems of the east has been proposed[2] and somewhat generally adopted:

Permian......	Dunkard formation (or series)	=Upper Barren Coal Measures
Pennsylvanian	4. Monongahela “ “ “	=Upper Productive Coal Measures
	3. Conemaugh “ “ “	=Lower Barren Coal Measures
	2. Allegheny “ “ “	=Lower Productive Coal Measures
	1. Pottsville “ “ “	

Distribution and Outcrops.

Between the Appalachians and the Rockies.—The distribution of the Pennsylvanian system as now exposed is shown in Fig. 240. The black areas represent the areas where the system is not covered, or covered only by drift, etc.; the lined areas represent regions where the system is believed to exist, though concealed; the areas marked by dashes represent regions where the presence of the system is more or less doubtful; while the dotted portions give some idea of the areas whence the system has been removed by erosion. The system is probably concealed over considerable areas to the south of those represented on the map, where the surface is occupied by younger formations, and its equivalent doubtless extends indefinitely under the sea.

It is not to be understood that the system everywhere contains coal in workable quantity, though within the areas indicated coal is widely distributed (Fig. 241), occurring as far west as the 96th or

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[1] Calvin, Bain, Beyer, Leonard, Young, and Keyes, Geol. Surv. of Iowa, Vols XIII, XI, VIII, VII, III, and I. See also Keyes, Am. Geol., Vol. 23, 1893, pp 298–316.

[2] Prosser, Am. Jour. Sci., 4th series, Vol. XI, p. 191, 1901.

97th meridian in Indian Territory,[1] and nearly to the 100th meridian in Texas.[2]

The distribution of the Pennsylvanian system in the eastern part of the continent, as it now appears at the surface, is in some ways in sharp contrast with the surface distribution of older systems. The commonest position for the outcrops of the Cambrian, Silurian, Devonian, and Mississippian systems severally is around the outcrops of older systems. But this rule does not seem to be followed in the case of the Pennsylvanian, the outcrops of which appear to exhibit no tendency to a similar concentric distribution. Rather do they seem to cover areas between the outcrops of older formations. Thus in Michigan, the Pennsylvanian strata occupy an area completely surrounded by older formations.

This difference in surface distribution does not betoken any real difference in the distribution of the system. The Ordovician formations come to the surface, among other places, in New York, Ohio, Wisconsin, Missouri, and the Black Hills. Beneath the surface, the beds outcropping in these several localities are believed to be continuous, though concealed by younger formations. It will be remembered that most of the eastern interior, and perhaps most of the west as well, became land at the close of the Ordovician period. Had it never again been submerged, the Ordovician system would not have been covered, and its outcrops would now have appeared at the surface not in zones about the exposed parts of earlier systems, but in broad areas between the outcrops of older formations; that is, these outcrops would have corresponded, in principle, with the surface distribution of the Pennsylvanian, so far as it appears at the surface. After the deposition of the Pennsylvanian system, the surface where it is now exposed was elevated, relatively, and except for the glacial drift, was either never deeply covered by later deposits, or if so covered, the overlying formations have been almost wholly removed.

The matter may be looked at in another way. The several land areas, which served as centers for the distribution of sediments, such as Appalachia, the Adirondacks, northern Wisconsin, etc., became, on the average, larger and larger as time went on; that is, the several land areas grew as the result of uplift, or withdrawal of the sea, in spite of the fact that they were periodically depressed and degraded, and so temporarily diminished in area. The result of the fluctuations of land and water appears to have been in the long run to the advantage of the land. If the apparent changes of level of the land were really due to its rising and sinking, the sum of the risings exceeded the sum of the sinkings. If, on the other hand, the apparent changes of level of the land were due to fluctuation of the level of the water, the *average* movement of its surface was downward. Before the Pennsylvanian period,[1] the Ohio island had made its appearance, and constituted a new sub-center of growth. With these several land areas gradually (on the average) enlarging, it is clear that the continuation of the process must ultimately have resulted in their union. Barring the Coastal Plain, that time came, so far as eastern North America is concerned, with the close of the Pennsylvanian period. While therefore the Pennsylvanian system of rocks really stands in much the same relation to the Mississippian system that each of the preceding systems does to its predecessor, its surface distribution seems to depart from the usual rule.

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[1] Gould, Am. Jour. Sci , Vol. XI, p. 185, 1901; and Taff, 22d Ann. Rept., p. 373, Pt. III.

[2] Taff, idem, p. 402.

Some of the separate areas of the system shown in Fig. 240 have probably been isolated since their deposition. Thus the eastern interior coal-field (Illinois-Indiana area, Fig. 241) may have been continuous with the western interior field (Iowa-Missouri-Arkansas area), the separation having been effected by erosion along the Mississippi, where the Coal Measures have been removed and the Mississippian formations below exposed. These two coal-fields are separated by a broad low anticline,[2] the existence of which allowed the Mississippi River to reach the Mississippian series the more readily in its down-cutting. The Coal Measures of different parts of Pennsylvania (Fig. 240), where the considerable altitude has favored erosion, have been isolated, though probably once continuous. The figure gives some idea of the extent of erosion in post-Carboniferous time. The Coal Measures of Pennsylvania may once have been continuous with those of the eastern Interior, via Kentucky and Tennessee, though this is uncertain. The Michigan[3] and Rhode Island[4] areas (the latter

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[1] Foerste, Bull. Geol. Soc. Am., Vol. XII, pp. 398–444.

[2] Hayes, 22d Ann. Rept. U. S. Geol. Surv., Pt. III, p. 16.

[3] Lane, ibid., pp. 307–331, and Repts. of the Michigan Geol. Surv.

[4] Shaler, Woodworth, Foerste, Mono. XXXIII, U. S. Geol. Surv.

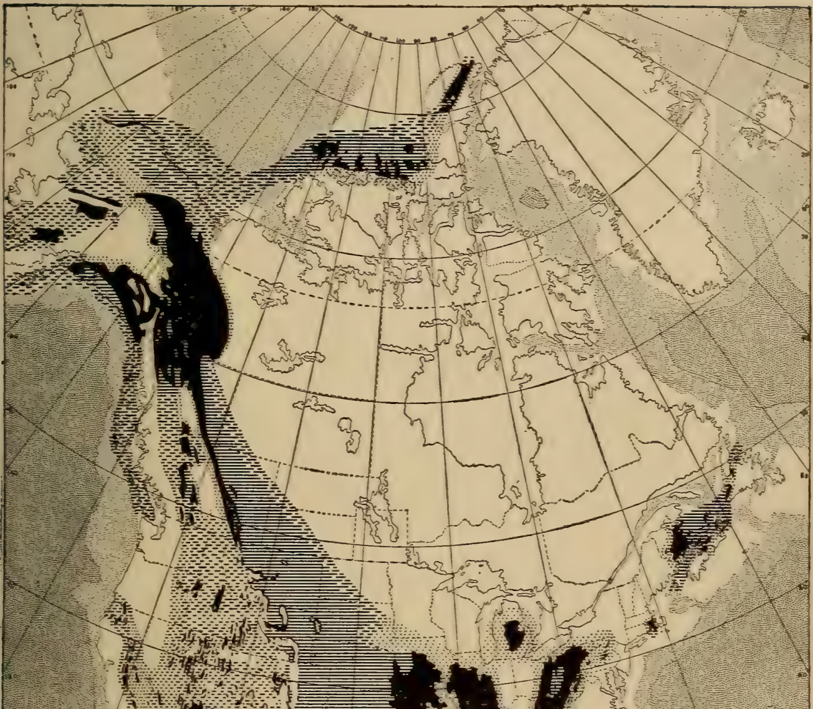

FIG. 240.—Map showing the areas where the Pennsylvanian system appears at the surface in North America. The map also shows, as in preceding similar cases, the areas where the Pennsylvanian system is thought to exist though buried (lined areas); the areas where it is thought once to have existed, but to have been removed by areas (dotted); and by inference the relations of land and sea during the Pennsylvanian period.

not shown in Fig. 241) were probably isolated from the beginning, though at the outset the latter was considerably, and the former somewhat, larger than now. It is to be understood that, as in the case of all other systems, the present margins of the Coal Measures are not the original margins. At many points, as in Iowa, Tennessee, and elsewhere, there are small outliers of Pennsylvanian formations which show that the system once extended beyond its present borders.[1]

Productive Coal-fields.

The productive coal areas of the Pennsylvanian (Carboniferous) system in the United States are five in number. These are as follows:[2]

(1) *The anthracite field,*[3] which is confined to eastern Pennsylvania, and contains an area of 484 square miles. This aggregate area includes several elongate, nearly parallel, synclinal basins, the longer axes of which have a northeast-southwest direction (Figs. 241 and 266). From the adjacent anticlines, and from the neighboring shallower synclines, the coal-bearing beds have been removed by erosion. The strata of this field may once have been continuous with those of the next.

(2) *The Appalachian field,*[4] which extends from the northern border of Pennsylvania to central Alabama, a distance of about 850 miles (Fig. 240), embraces an area of about 70,800 square miles, of which about 75 per cent contains workable coal. Speaking in general terms, the western edge of the sharply folded Appalachian belt forms the eastern edge of the Appalachian coal-field. Barring a few outlying synclines to the east, the strata of this field are gently undulating or horizontal. The formations thicken to the east and thin to the west. Few beds of coal are known to have great extent, but the Pittsburg bed in the Monongahela series, and the Sewanee bed in the Pottsville series, seem to be continuous over areas of several thousand square miles.

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[1] For details, see the geological reports of the States where the Carboniferous system is present. Summaries of classifications for Kansas and Nebraska are given (Prosser) in Jour. Geol., Vol. VII, pp. 342–56, and Vol. X, pp. 703–17.

[2] Hayes, 22d Ann. Rept., U. S. Geol. Surv. Pt. III, p. 15.

[3] Stoek, idem, pp. 61–117. Also Geol. Surv. Repts. of Pennsylvania.

[4] Idem, White (D.), Campbell (M. R.), Hayes, and Haseltine, pp. 127–263. Also State Geol. Surv. Repts. of Pennsylvania, Ohio, Maryland, West Virginia, Kentucky, Tennessee, Alabama.

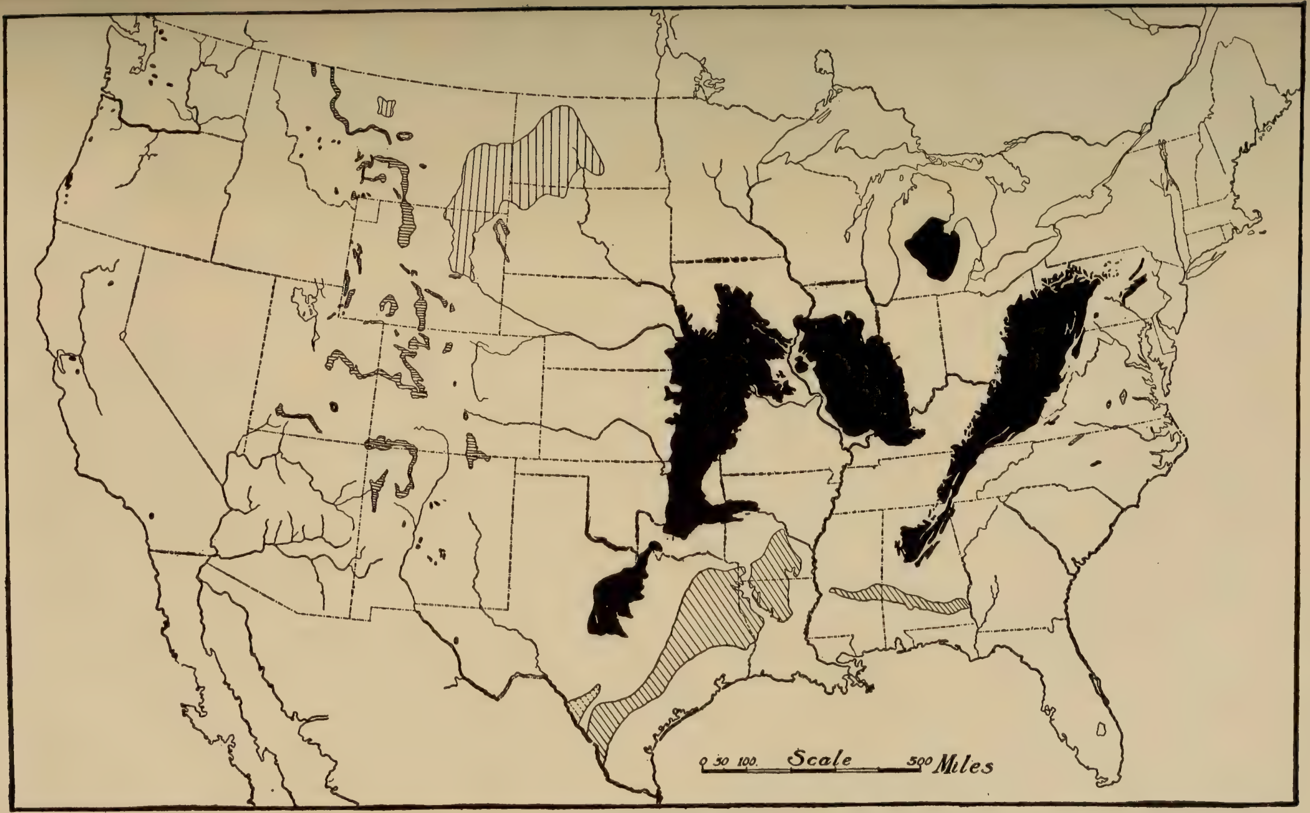

FIG. 241.—Map showing the known distribution of coal in the United States. The black areas are the areas within which coal of the Pennsylvanian system (anthracite and bituminous) occurs. The areas marked by dots in Virginia and North Carolina, represent Triassic (bituminous) coal. Those with vertical (lignite) and horizontal (anthracite, bituminous, and lignitic-bituminous) lines represent coal of the Cretaceous (Laramie) system, and those with diagonal (lignite) and crossed (bituminous and lignitic-bituminous) lines represent coal fields of Tertiary age. The Cretaceous and Tertiary areas include only those where there is known to be workable coal. (U. S. Geol. Surv.)

(3) *The Northern Interior field,*[1] which is confined to the southern peninsula of Michigan and covers an area of about 11,000 square miles. The strata of this field appear to dip gently toward the center of the basin (i.e. toward the center of the Lower Peninsula), but the field is so heavily covered with glacial drift that its structure is less well known than that of the other fields. The formations of this basin were probably never connected with those of the other coal-fields.

(4) *The Eastern Interior field*[2] covers an area of about 58,000 square miles in Indiana, Illinois, and Kentucky (Fig. 241). About 55 per cent of the area is productive. About its borders, the beds of the series are gently inclined, generally toward the center, while in the central part they are nearly horizontal. This field is set off from the Appalachian field on the east, and from the Western Interior field on the west, by broad low anticlines from which the Coal Measures, if ever present, have been eroded. The former connection of this field with that to the west is probable.

(5) *The Western Interior and Southwestern fields*[3] constitute a nearly continuous area of Coal Measures formations, stretching from northern Iowa to central Texas, a distance of 800 miles, and covering an area of 94,000 square miles, including parts of Iowa, Nebraska, Missouri, Kansas, Arkansas, Indian Territory, and Texas. On the east this field is limited by the broad low anticline which borders the Eastern Interior field on the west. On the west the field is limited by the overlap of younger formations. Except in Arkansas and Indian Territory, where the strata are folded, the beds of the Coal Measures of this area are essentially horizontal.

(6) *The Nova Scotian-New Brunswick coal-field.*—This lies on both sides of the Bay of Fundy and contains an area estimated at about 18,000 square miles. There are numerous beds of coal several of which are workable. The coal is bituminous and of good quality.

While the Pennsylvanian system was perhaps less widespread than the Mississippian, in the Mississippi basin, the less extensive system sometimes overlaps the more extensive, as shown on the map (p. 218), where the Pennsylvanian rests on formations older than the Mississippian. This is the case in Illinois,[1] Iowa,[2] Indian Territory,[3] and elsewhere. The absence of Mississippian formations in these several situations may be due either to failure of deposition, or to post-Mississippian-pre-Pennsylvanian erosion.

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[1] Lane, 22d Ann. Rept. U. S. Geol. Surv., Pt. III, pp. 313–331, and Repts. of the Geol. Surv. of Michigan.

[2] Ibid., Ashley, pp. 271–305, and Repts. of the Geol. Survs. of Indiana, Illinois, and Kentucky.

[3] Ibid., Bain and Taff, pp. 335–413. Also State Geol. Surv. Repts. of Iowa, Missouri, Kansas, Nebraska, Arkansas, and Texas.

Figs. 242 and 243 illustrate further the constitution of the system in the east, and Fig. 244 its structure at a point in the western part of the Appalachian Mountain system.

East of the Appalachians.—The Carboniferous system occurs in the vicinity of Narragansett Bay,[4] where it has an aggregate thickness of about 12,000 feet, and often rests on beds of Cambrian age. The Mississippian system appears to be wanting in this region, thus affording another bit of evidence of the distinctness of the Pennsylvanian and Mississippian periods. The Pennsylvanian system of this region carries coal, which is, however, too highly anthracitic (or graphitic) to burn readily. The beds are much deformed and locally highly metamorphosed. They are associated with igneous rocks, some of which are pre-Carboniferous.

Carboniferous rocks of undetermined extent occur at other points in New England,[5] where they are partly igneous (Fig. 245) or meta-igneous, and partly meta-sedimentary. They are sometimes so completely metamorphic as to make the determination of their age and relations difficult and uncertain.

Northeast of New England, in Cape Breton, Nova Scotia, and New Brunswick, the Pennsylvanian system is extensively developed. Its general constitution, including rich beds of coal, is similar to that of the corresponding system in the eastern part of the United States. From the nature of the formations, the existence of conditions similar to those in the eastern interior is inferred. In Nova Scotia the system attains a thickness of some 13,000 feet.

West of the Great Plains.—Formations made during the period when the Pennsylvanian system was accumulating in the east are

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[1] Reports of the Geol. Surv. of Illinois and geological map of Illinois.

[2] Reports of the Geol. Surv. of Iowa and geological map of Iowa.

[3] Coalgate folio, U. S. Geol. Surv.

[4] Shaler, Woodworth and Foerste, Geology of the Narragansett Basin, Mono. XXXIII, U. S. Geol. Surv.

[5] Emerson and Perry, Geology of Worcester, Mass.; also Perry, Jour. Geol., Vol. XII, p. 7.

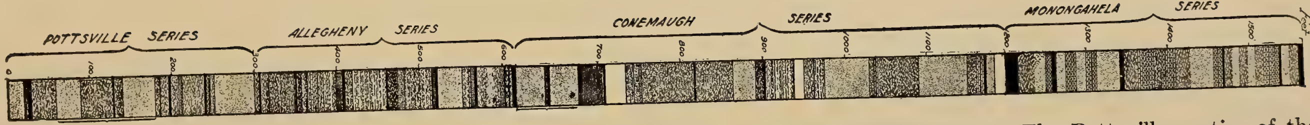

FIG. 242.—Composite section of the Pennsylvanian system of Pa. compiled from various sources. The Pottsville portion of the section is from Mercer Co. (I. C. White); the Allegheny portion from Armstrong Co. (White [David] and Campbell); the Conemaugh portion from Fayette Co. (I. C. White); the Monongahela portion from Fayette Co. The black bands represent coal, the checked pattern limestone, the dots sandstone, and the broken lines shale (Stevenson). (U. S. Geol. Surv.)

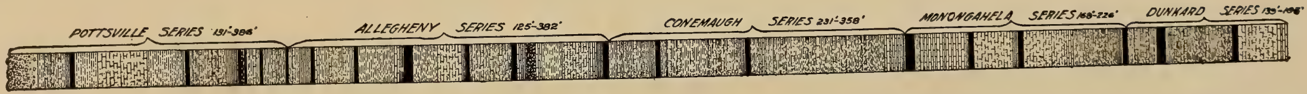
POTTSVILLE SERIES 131'-386'
ALLEGHENY SERIES 125'-382'
CONEMAUGH SERIES 231'-358'
MONONGAHELA SERIES 168'-226'
DUNKARD SERIES 135'-195'

FIG. 243.—Section of the Coal Measures in Ohio. The conventions are as in Fig. 242 (Haseltine, U. S. Geol. Surv.).

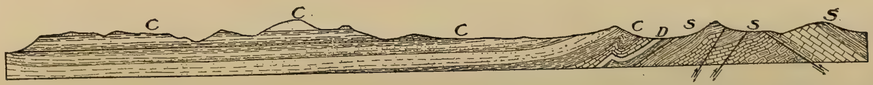

FIG. 244.—Section showing the position and relations of the Carboniferous section near Estillville, Ky. C=Carboniferous (including Mississippian); D=Devonian; S=Silurian. Length of section about 16 miles (Campbell, U. S. Geol. Surv.).

widespread west of the Great Plains, and probably underlie the Plains themselves. With rare exceptions, these western beds, largely of limestone and sandstone, represent the coal-less phase of the Pennsylvanian (Upper Carboniferous) system, a phase which is far more widespread, the whole earth considered, than the coal-bearing phase. There is probably no other continent where the rocks of the period are so generally coal-bearing as in North America; yet even here the coal-less phase of the system is probably more extensive than the coal-bearing. The abundant coal of the west does not belong to this system, but to later ones (Cretaceous and Tertiary). While therefore there are large areas where coal constitutes a part of the Carboniferous system, the formations of this period do not all contain coal, nor are all workable coal deposits referable to this period. In this case, as in others yet to be described, the exceptional and relatively local phase has been taken for the type, partly because it was the part first studied, and partly because it is of great industrial importance.

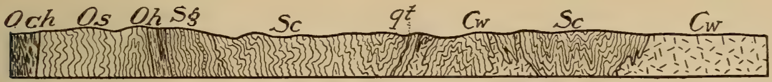

FIG. 245.—Section in southwestern Massachusetts, showing the position and relations of the Carboniferous system. *Cw* = igneous rock, Carboniferous; *Sc* (Conway schist) and *Sg* (Goshen schist) are Silurian formations; *Oh* (Hawley schist), *Os* (Savoy schist) and *Och* (Chester Amphibolite), are probably Ordovician, though classed with the Silurian in the Hawley folio. (Emerson, U. S. Geol. Surv.).

The Mississippian and Pennsylvanian systems have not always been differentiated west of the Great Plains. With rare exceptions, the formations of this system (or of the two systems together) are such as to indicate that marine conditions prevailed in the west. Locally at least (p. 508), sedimentation was interrupted at the close of the Mississippian period, and the tendency of the rapidly increasing knowledge of the west is toward the view that unconformity between the Lower and Upper Carboniferous is somewhat widespread.[1] Furthermore, the formations of the Pennsylvanian period are not in general so widespread as those of the Mississippian, thus affording evidence as significant as that of unconformity of the geographic changes of the time.

From the nature of the formations, it is clear that sedimentation in the western part of the continent was effected under conditions very different from those which prevailed farther east. In the region of productive coal, marine conditions seem to have recurred more frequently and to have been of longer duration in the western coal-fields than in the eastern. These relations suggest that now and again the marine conditions of the west extended to the east, as the result of subsidence in that direction, though it does not appear that the sea-water at any time became deep within the regions where the coal occurs. On the other hand, it now appears that the conditions of the east sometimes prevailed, at least locally, in the west, for carbonaceous beds, and even beds of coal, are known in the system in Arizona[1] and perhaps in New Mexico.[2] In some parts of the west, the Carboniferous system includes formations which closely resemble the "Red Beds" of the Permian. This is true, for example, in some parts of Nevada,[3] where the separation of the Pennsylvanian system from the Permian is not very distinct, or has not been carefully worked out.

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[1] See foot-note, p. 510.

The Carboniferous (Pennsylvanian) system of the west includes all sorts of sedimentary rocks, among which are considerable thicknesses of limestone. They are exposed at many points (Fig. 240) and their existence over wide areas where they are now covered by later deposits is certain. The Carboniferous of the west is, however, not continuous. Numerous islands of older rock probably maintained themselves throughout the period, and a large area of land existed throughout the Paleozoic era in western Nevada (west of long. 117°) and had an unknown extension north and south.

In the Carboniferous system of some parts of Colorado (Elk Mountains and Sangre de Cristo range) and New Mexico, there is a notable unconformity, with great accumulations of conglomerate,[4] 3,000 to 6000 feet thick, at the base of the upper (probably Pennsylvanian) system. Some of the bowlders of the conglomerate are said to be 50 feet in diameter. The unconformity seems not to be universal, and the conglomerate is, so far as known, rather local. Both phenomena have been attributed to notable orogenic movements, and to the great erosion which followed. Beds of finer sediment succeed the conglomerate. On the basis of fossils, the older beds of the Pennsylvanian system in Colorado are thought to be older than the basal beds of the same system in Nebraska and Kansas.[1]

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[1] Blake, Am. Geol., Vol. XXVII, 1901, p. 161; also Dumble, Am. Geol., Vol. XXX, p. 270.

[2] Southwest of Las Vegas, unpublished evidence.

[3] Spurr, Bull. 208, U. S. Geol. Surv., pp. 166–173.

[4] Emmons, Orogenic Movements in the Rocky mountains, Bull. Geol. Soc. Am., Vol. I.

West of the Great Plains the outcrops of the Carboniferous strata often occur about the areas of older rock, where uplift and erosion have exposed them. They appear as narrow borders about various mountain ranges in South Dakota, Montana (mostly Mississippian), Idaho, Wyoming[2] (where submergence was much more extensive in the Pennsylvanian than in the Mississippian period), and Colorado. Some of the fault-block and monoclinal[3] mountains of the west are composed largely of Carboniferous limestone, and here the outcrops cover large areas. The same formations appear at the surface in large areas, in the southwest, especially Arizona, not in immediate association with mountains (Fig. 240). In Nevada, the Carboniferous (Mississippian or Pennsylvanian) formations rest on Cambrian or Ordovician with apparent conformity.[4]

Figs. 246 to 251 show the positions and relations of the Mississippian and Pennsylvanian systems at various points in the west. In most cases the sections are from regions where the strata have been much disturbed by folding, faulting, and the irruption of igneous rock. In all cases the Carboniferous beds are indicated by *C*, or some combination of letters beginning with *C*. Fig. 246 shows the Carboniferous system of the Black Hills, somewhat deformed, resting on the Cambrian, and largely covered by younger formations. Fig. 247 shows the relations of the systems in the Yellowstone Park; Fig. 248 (Colo.) shows the system affected by igneous rock; Fig. 249 (Utah) shows the system where it has been notably affected by intrusions of igneous rock, the latter having, in its ascent, torn off and included masses of the stratified rock; Fig. 250 (Ariz.) represents a section where faulting has produced complicated stratigraphic relations; while 251 (Cal.) shows the system where it is notably deformed and metamorphosed. Figs. 244 and 245 show the system in still other relations.

West of the Paleozoic land area, which, in the vicinity of the 40th

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[1] Girty, Professional Paper, No. 16, pp. 258–267.

[2] Knight, Bull. 45, Wyoming Experiment Station, 1900.

[3] Keyes, Am. Jour. Sci., Vol. XV, 1903, p. 207.

[4] Weeks (cited by Spurr) and Spurr, Bull. 208, U. S. Geol. Surv., pp. 32 and 166–172.

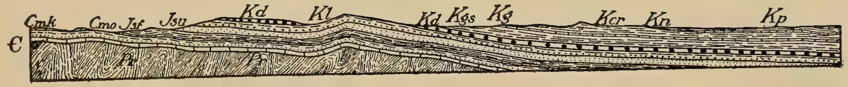

FIG. 246.—Section showing the structure and relations of the Carboniferous in the southern part of the Black Hills region of South Dakota. *Pr* = Proterozoic; *Cmk* (Minnekahta limestone) and *Cmo* (Opeche formation) = Carboniferous; *Jsf* (Spearfish shale) and *Jsu* (Unkpapa sandstone) = Jurassic; *Kd* (Dakota), *Kgs* (Graneros shale), *Kg* (Greenhorn limestone), *Kcr* (Carlile formation), *Kn* (Niobrara formation), and *Kp* (Pierre shale) = Cretaceous. Length of section about 12 miles. (Darton, U. S. Geol. Surv.)

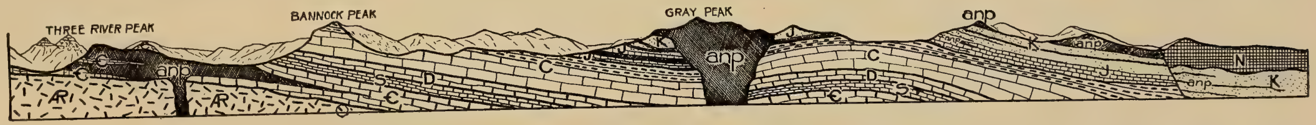

FIG. 247.—Section shows position and relations of the Carboniferous system (as well as others) in the Yellowstone Park. *Æ* = Archean, *Ꞓ* = Cambrian, *S* = Ordovician and Silurian, *D* = Devonian, *C* = Carboniferous, *J* = Jurassic, *K* = Cretaceous, *N* = Neocene, and *anp* = igneous rock. Length of section about 17 miles. (Hague, Iddings, and Weed, U. S. Geol. Surv.)

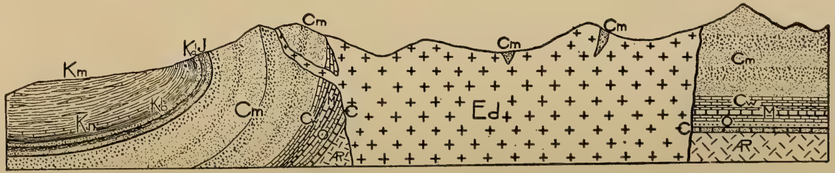

FIG. 248.—Section showing the position and relations of the Carboniferous system at a point in Colorado. *Æ* = Archean; *Ꞓ* = Cambrian (Sawatch quartzite); *O* = Ordovician (Yule limestone); *M* = Mississippian (Leadville limestone); *Cw* (Weber formation) and *Cm* (Maroon conglomerate) = Carboniferous; *J* (Gunnison formation) = Jurassic; *Kd* (Dakota formation), *Kb* (Benton shale), *Kn* (Niobrara limestone), and *Km* (Montana formation) = Cretaceous. Length of section about 6 miles. (Eldredge, U. S. Geol. Surv.)

parallel, lay west of the 117th meridian, Carboniferous strata are known at various points. They make up the body of the Blue mountains in Oregon,[1] they occur in the Klamath mountains of northern California and southern Oregon,[2] at many points in the western portion of the Sierras in California,[3] and probably in the Cascade Mountains of Washington.[4] It is possible that the Carboniferous seas surrounded the great land area which lay between longitude 117° and 121° in the vicinity of the 40th parallel, and which had an unknown extension north and south.

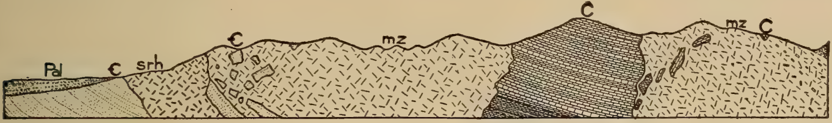

FIG. 249.—Section showing the relations of the Carboniferous system at one point in the vicinity of Tintic, Utah. Ꞓ (Tintic quartzite) = Cambrian; *C* (Mammoth limestone) = Carboniferous; *mz* (monzonite) and *srh* (rhyolite) = igneous rock; *Pal* = alluvium. The section shows that much of the sedimentary rock was disturbed and displaced by the extrusion (or intrusion) of the lava. Length of section about 3 miles. (Tower, U. S. Geol. Surv.)

North of the United States, Carboniferous strata (largely Lower Carboniferous) outcrop on the west side of the northward continuation of the Great Plains,[5] and perhaps on the east. The strata of these belts are probably continuous beneath the younger strata which occupy the surface between them and they are probably also con-

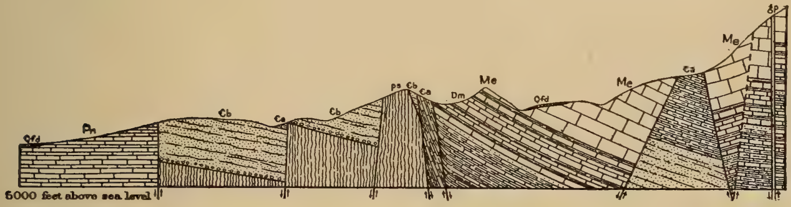

FIG. 250.—Structure near Bisbee, Ariz. *ps* = pre-Cambrian; *Ꞓb* and *Ꞓa* = Cambrian; *Dm* = Devonian; *Me* = Mississippian; *Ca* = Pennsylvanian; *Qfd* = Quaternary; *gp* = granite porphyry (Triassic or Jurassic). Length of section, a little more than one mile. (Ransome, U. S. Geol. Surv.)

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[1] Lindgren, Science, Vol. XIII, N. Ser. 1901, p. 271.

[2] Diller, Am. Jour. Sci., Vol. XV, p. 348, 1903.

[3] Folios U. S. Geol. Surv., and King, Geol. Surv. of 40th Parallel, Vol. I.

[4] Smith, G. O. Mount Stuart, Wash., folio, U. S. Geol. Surv.

[5] Dawson, Science, March 15, 1901.

tinuous to the southward with the Carboniferous formations of the United States.

The system is widespread on both sides of the Gold range of British Columbia. West of that range, the formations of the system (including the Lower Carboniferous) contain much volcanic rock, the greater part of which was extruded before the close of the period. The igneous activity of the time extended northward beyond the boundaries of British Columbia into the little-known Northwest Territory,[1] and southward into the United States. The Pennsylvanian system[2] is continued northward into Alaska, where it is less wide-spread than the Mississippian so far as present knowledge goes. In the arctic regions of America, the Mississippian and Pennsylvanian are not differentiated, but one or both are believed to be somewhat widespread. The same systems also find meager representation in Mexico and Central America.

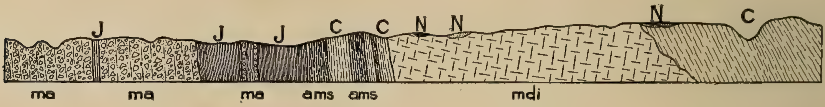

FIG. 251.—Section showing the Carboniferous in the Sierras of central California. *C* (Calaveras formation) = Carboniferous; *J* (Mariposa slates) = Jurassic; *mdi* = metadiorite; *ams* = amphibolite schist; *N* = igneous rock of various sorts, of Neocene age. Length of section about 6½ miles. (Ransome, U. S. Geol. Surv.)

Sections of the Mississippian and Pennsylvanian Systems.

The following sections of the Pennsylvanian system (together with the Mississippian and in some cases the Permian) at various points within the United States, supplement those given in the Appendix and give some idea of the range, variations, and relations of the system:

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[1] Dawson, Science, March 15, 1901.

[2] Brooks, Professional paper, p. 19.

SECTION IN NORTHERN PENNSYLVANIA.[1]

	Names of Formations.	Thickness in Feet.	Characteristics.
Pennsylvanian.	Summit removed by erosion		
	Pottsville formation. . . .	200	Sandstone, black shale, and fire-clay, with a three-foot coal-bed in the upper part.
	Sharon conglomerate. . . .	60–100	White quartz conglomerate and sandstone.
	Unconformity.		
Mississippian.	Mauch Chunk shale.	0–40?	Red shale.
	Oswayo formation	1000 ±	Varicolored sandstone and shales.
	(Lower part of Oswayo probably Devonian.)		

SECTION IN SOUTHWESTERN PENNSYLVANIA.[2]

	Names of Formations.	Thickness in Feet.	Characteristics.
Permian.	Summit removed by erosion		
	Dunkard series	400 +	Blue to black limestone, weathering white; coarse sandstone at the base; contains a number of thin coal-beds.
Pennsylvanian.	Monongahela series	380 ±	Blue limestone with calcareous shale-beds; lentils of sandstone and coal; the most important coal-bearing formation in southwestern Pennsylvania, and contains the Pittsburg coal seam.
	Conemaugh series	590 ±	Chiefly red and green shales, with interstratified beds of coarse sandstone and thin beds of coal.
	Allegheny series.	270 ±	Shales, sandstone, and three important coal-beds.
	Pottsville sandstone . . .	180 ±	Generally coarse hard sandstone or conglomerate, inclosing a thin irregular bed of shale; equivalent to the uppermost beds of the Pottsville formation in the type locality.
	Unconformity.		
Mississippian.	Mauch Chunk shale.	250	Red and green shales with beds of greenish sandstone, inclosing a lentil of blue fossiliferous limestone, which is the thin edge of the Greenbrier limestone of Virginia.
	Pocono sandstone.	300 +	Sandstone, varying from thin-bedded flaggy rock to coarse irregularly bedded conglomerate; beds of silicious limestone at the top.
Devonian.			

Strata in broad gentle folds.

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[1] Fuller, Gaines (Penn.) folio, U. S. Geol. Surv.

[2] Campbell, Masontown-Uniontown (Penn.) folio, U. S. Geol. Surv

GENERALIZED SECTION FOR WEST VIRGINIA.[1]

	Names of Formations.	Thickness in Feet	Characteristics.
Permian.	Dunkard series.	1020	Red shales, massive sandstones, thin limestones, and a few thin beds of coal; rocks slightly gypsiferous; fresh-water deposits.
Pennsylvanian.	Monongahela series.	381	Much limestone; a little red shale; some massive sandstones, one of which is the the uppermost "oil sand" yet developed in the Appalachian field; five coal-beds, the most important of whichis the Pittsburg seam; Permo-Carboniferous flora; fresh-water fauna.
	Elk River series or Barren Measures. (Corresponds to Conemaugh series.)	584	Much red shale in upper two thirds; Permo-Carboniferous fauna and flora; thin limestones, three or four thin coal-beds; several important sandstone beds, two of which carry oil. Lower half of series of marine or littoral origin.
	Allegheny (including Kanawha) series.	264	Dark shales and gray sandstones, with five important coal-beds and two or three thin beds of limestones; one oil and gas horizon; marine fossils; typical Coal Measures flora.
	Pottsville conglomerate.	200–1500	Massive pebbly sandstones, usually bearing salt water; separated by dark shales which hold thin coal seams at the north and important ones at the south.
	Unconformity.		
Mississippian.	Mauch Chunk shales.	150	Soft red shales interstratified with green sandstones and impure limy beds. Series thins and disappears westward; thickness given is for Monongahela and Marion Counties.
	Mountain or Greenbrier limestone.	90	Hard gray limestone.
	Pocono sandstone.	200	Big Injun oil sand, including Keener sand horizon at the top; one of the most important oil and gas horizons in the State.
Devonian.		380	Shales and sandstones, including Smith's Ferry oil sand, and possibly Berea.

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[1] White, West Virginia Geol. Surv., Vol. I, p. 212. The section for Maryland is very similar to the above. See Prosser, Jour. of Geol., Vol. IX, pp. 422–429.

SECTION IN WESTERN VIRGINIA.[1]

	Names of Formations.	Thickness in Feet.	Characteristics.
Pennsylvanian.	Summit removed by erosion.		
	Wise formation	100+	Shale, sandstone, and coal-beds.
	Gladeville sandstone	100	Coarse sandstone, locally conglomeratic.
	Norton formation	1200–1300	Shale, sandstone, and coal-beds; the important coal-bearing formation of the region.
	Lee formation	1500±	Coarse massive conglomerate; shale with coal-seams; sandstone, generally free from pebbles, with shale layers; shale with coal-seams; massive sandstone.
	Unconformity.		
Mississippian.	Pennington shale	1040–1100	Red and green argillaceous shale; occasional beds of sandstone and impure limestone.
	Newman limestone	1000±	Calcareous shale with beds of impure limestone; heavy-bedded, blue limestone, slightly cherty toward the base.
	Grainger formation	1000–1500	Argillaceous and calcareous shale; sandy shale, and thin-bedded sandstone.
	The lower part of this formation is Devonian.		

Strata folded and faulted.

SECTION IN SOUTHERN WEST VIRGINIA AND WESTERN VIRGINIA.[2]

	Names of Formations.	Thickness in Feet.	Characteristics.
Pennsylvanian.	Upper part wanting.		
	Charleston sandstone	500+	Coarse sandstone with beds of coal.
	Kanawha formation	1000±	Sandy and argillaceous shales; soft sandstone, and numerous seams of coal, many of workable thickness.
	Guyandot sandstone	10–100	Coarse sandstone or conglomerate (lentil).
	Harvey conglomerate	0–50	Massive conglomeraate (lentil).
	Sewell formation	650–700	Sandy and argillaceous shale and sandstone.
	Raleigh sandstone	300	Coarse sandstone in heavy beds.
	Quinnimont shale	300	Shale with thin beds of sandstone and a few coal-seams; Quinnimont coal-bed.
	Clark formation	380	Sandstone with some shale and coal-beds.
	Pocahontas formation	360	Pocahontas (No. 3) bed of coal; gray and green argillaceous sandstone and shale.
Mississippian.	Bluestone formation	800	Purple shale and thin red sandstone, with calcareous beds, sometimes taking the form of limestone conglomerate.
	Princeton conglomerate	40	Coarse sandstone or conglomerate; calcareous matrix locally.
	Hinton formation	1250–1300	Purple shale, green and purple sandstone, and impure limestone or calcareous shale.
	Bluefield shale	1250–1350	Blue limestone and calcareous sandstone; calcareous shale.
	Greenbrier limestone	1500	Alternating shale, and heavy-bedded, blue fossiliferous limestones; heavy beds at base carry black chert.
	Pulaski shale	20–300	Bright red or purple.
	Price sandstone	200–300	Coarse yellow sandstone interbedded with sandy shale and coal-beds.

Strata gently folded.

[1] Campbell, Bristol, Va.-Tenn. folio, U. S. Geol. Surv. Unconformity between the Pennington and Lee formations is implied, but not affiirmed, in the text of this folio.

[2] Campbell, Pocahontas, Va.-W. Va. folio, U. S. Geol. Surv.

SECTION IN EAST-CENTRAL KENTUCKY.[1]

	Names of Formations.	Thickness in Feet.	Characteristics.
Pennsylvanian.	Summit removed by erosion.		
	Corbin conglomerate	90	Coarse pink sandstone or conglomerate (lentil).
	Unconformity.		
	Lee formation	250–300	Shale and sandstone with coal-beds; outcrops of coal are of limited extent; rests on Pennington shale in places.
	Rockcastle conglomerate lentil		Coarse conglomerate, unconformable on the Pennington shale or on Newman limestone.
	Unconformity.		
Mississippian.	Pennington shale	0–90	Red and green, with thin beds of limestone.
	Newman limestone	100–200	Blue, slightly cherty near the base.
	Waverly formation	350–420	Fine green shale with iron concretions; green, calcareous, and argillaceous sandstone.
	Devonian.		

Strata nearly horizontal.

SECTION FOR OHIO.[2]

	Names of Formations.	Thickness in Feet.	Characteristics.
Permian.	Dunkard series	525	Sandstone, generally massive; shales, limestones, and thin coal-beds; beds nonmarine at least in part.
Pennsylvanian.	Monongahela series	200–250	Shales, limestones, and sandstones; important coal-beds.
	Conemaugh series	400–500	Upper part mainly shales; lower part sandstones, with some shale and limestone.
	Allegheny series	165–300	Shales, limestones, and sandstones, with important coal-beds.
	Pottsville conglomerate	250 ±	Light-colored sandstones and conglomerates, with some shale and a few coal-beds.
	Unconformity.		
Mississippian.	Maxville limestone	25 ±	Fossiliferous limestone, often brecciated.
	Logan group	100–150	Sandstone, massive conglomerate, and shale.
	Black Hand conglomerate	50–500	Sandstone and fine conglomerate.
	Cuyahoga shale	150–300	Light-colored, argillaceous, with thin sandstone bands; shales contain ferruginous nodules.
	Sunbury shale	5–30	Black bituminous shale.
	Berea grit	10–135	Sandstone, important for building purposes and for grindstones; locally a repository for oil, gas, and brine.
	Bedford shale	50–150	Thin-bedded shales, with occasional thin beds of sandstone.
	Devonian.		

Strata dip at low angles.

[1] Campbell, Richmond (Ky.) folio, U. S. Geol. Surv.

[2] Prosser, Jour. of Geol., Vol. XI, pp. 520–521; Orton, Geol. Surv. of Ohio, Vol. VI, pp. 33–39

SECTION IN NORTHERN MISSOURI.[1]

		Names of Formations.	Thickness in Feet.	Characteristics.
Pennsylvanian.	Missouri Series.	(Not subdivided)	1000	Shales and limestones, the former predominant.
			150	Shale and sandstone.
			90	Shale and limestone.
			100–400	Shale and sandstone.
	Des Moines Series.	Pleasonton shales.	150	Shale and sandstone; occasional thin beds of concretionary limestone, and one or two thin beds of coal.
		Henrietta formation.	90	Shales, resistant limestones, sandstones, and clays; one or two beds of coal of commercial importance.
		Cherokee shales.	100	Conglomerate at the base, grading into sandstone above and this into shale; coal-beds and occasional beds of limestone of limited extent.
		Unconformity. **Discontinuity.**		
Mississippian.	Kaskaskia.	Kaskaskia limestone	200	Thin beds of gray limestone and bluish marl, rich in fossils.
		Aux Vases sandstone	80	Fine-grained ferruginous.
	St. Louis.	St. Genevieve limestone	50	Thick-bedded.
		St. Louis limestone	150	Heavy-bedded, gray, oölitic at base.
		Warsaw formation	80–100	Gray and bluish-gray limestone; fossils numerous.
	Augusta.	Keokuk formation	50	Limestone, massive, compact, white in color and highly fossiliferous.
		Discontinuity.		
		Upper Burlington limestone	50	Thin-bedded at the top, more massive, encrinital below; cherty.
		Lower Burlington limestone		White, bluish or brown in color; heavy-bedded; largely encrinital.
		(Unnamed)	9	Yellow, massive or thick-bedded, rather soft, fine-grained limestone.[2]
	Kinderhook.	Hannibal shales	72	Green, sandy above; brown, sandy, grading into soft sandstone.
		Louisiana limestone	48	Buff to gray, compact, fine-grained in thin layers; similar to lithographic stone in texture.
Devonian.				

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[1] Pennsylvanian section is generalized for the northern part of the state; Marbut, Missouri, Geol. Surv., Vol. XII, pp. 267–269. The Mississippian section, above the Keokuk, is for St. Genevieve Co.; Shumard, Geol. Surv. of Missouri, 1855–71, pp. 292–293, and Keyes, Missouri, Geol. Surv., Vol. IV, p. 48. Below the Keokuk, the section is that exposed at Louisiana, Mo.; Proc. Iowa Acad. Sci., 1896, Vol. IV, pp. 26–27.

[2] This bed has been correlated with the Chouteau limestone which is well developed in central and southwestern Missouri, but this correlation is probably incorrect.

SECTION IN ARKANSAS.[1]

Names of Formations.			Thickness in Feet.	Characteristics.
Pennsylvanian.[1]		Potean beds	3500	Not described in detail.
		Productive beds	1800	Mainly shales and sandstones with some coal-beds.
		Barren beds	18480	
		Discontinuity.		
		Millstone grit	500	Sandstones and conglomerates; friable to hard and compact; buff or brown; occasionally thin seams of limonite.
Mississippian.	Boston series.	Kessler limestone	3–15	Thin-bedded.
		Coal-bearing shale	60–90	Highly fossiliferous; coal seams 6–14 inches thick.
		Pentremital limestone	0–90	Impure, dark-colored, loose-textured; sometimes interbedded with sandstone.
		Washington sandstone and shale	40–75	Sandstone and gray shale in varying proportions.
		Archimedes limestone	0–80	Light gray limestone, rich in Archimedes.
		Marshall shale	0–250	Black, bituminous shale.
		Batesville sandstone	10–200	Sandstone, sometimes massive cross-bedded in places.
		Spring Creek black shale and limestone	300	Black to bluish or yellowish brown in color.
		Wyman sandstone	0–9	Sandstone, rather soft.
		Boone chert (including St. Joe marble)	370	Interbedded strata of chert and limestone in varying proportions; contains St. Joe marble, 25–40 feet.
		Sylamore sandstone	0–40	Hard or saccharoidal sandstone and thin-bedded black shale; phosphates.
		Eureka shale	0–50	
		Unconformity.		
Silurian.				

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[1] The section above the Millstone Grit is for the Arkansas River valley; that below, for the northern part of Arkansas. Adams, 22d Ann. Rept., U. S. Geol. Surv., Pt. II, pp. 83–89; Simonds, Ark. Geol. Surv., Ann. Rept. 1888, Vol. IV, pp. 26–106; Hopkins, ibid. 1890, Vol. IV, pp. 90–94, 253; Penrose, ibid. 1890, Vol. I, pp. 129–139; Williams, ibid. 1892, Vol. V, pp. 273–322; Branner, Am. Jour. Sci., 4th series, Vol. II, 1896 p. 235.

SECTION IN NORTHERN TEXAS.[1]

	Names of Formations.	Thickness in Feet.	Characteristics.
Pennsylvanian.	Albany division.	0–1180	Thick beds of limestone, generally separated by shaly layers.
	Cisco division.	840	Shales, with thin beds of limestone, sandstone, conglomerate and coal.
	Canyon division.	800–930	Limestone and shale with local beds of sandstone and conglomerate; no coal.
	Straw division.	950–3700	Sandstone and shale; no coal.
	Millsap division.	1000	Blue and black shale interstratified with occasional limestone and sandstone strata.
	Ordovician?		

SECTION IN WEST-CENTRAL COLORADO.[2]

	Names of Formations.	Thickness in Feet.	Characteristics.
	Jura-Trias		
	Unconformity.		
Pennsylvanian.	Maroon conglomerate	2500	Conglomerate and sandstone in heavy beds; material is derived chiefly from the Archean, but some of the conglomerate contains limestone pebbles derived from the Mississippian beds; occasional thin beds of fossiliferous limestone.
	Faunal break.[3]	2000	Quartzose conglomerate, grit and sandstone, with varying amounts of pebbles derived from the Weber and Leadville formations, sometimes forming the bulk of the deposit; thin interbedded layers of fossiliferous limestone.
	Weber limestone.	100–550	Dark gray to black shale, with limestone beds carrying black chert.
	Unconformity.		
Mississippian.	Leadville limestone.	400–525	The upper third massive, blue and cavernous; lower two thirds bedded gray to brown; dark cherts.
	Silurian.		

Rocks faulted and somewhat folded.

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[1] Cummins, Geol. Surv. of Texas, 2d Ann. Rept., pp. 361–375.

[2] Eldridge, Anthracite-Crested Butte (Colo.) folio, U. S. Geol. Surv.

[3] Girty, Professional Paper No. 16, pp. 258–267.

The Coal.

The general conditions under which sandstone, shale, and limestone originate have already been stated, and need not be here repeated, but in the discussion of the formations of the preceding periods there has been no occasion to consider the formation of coal. From its economic importance, this sort of rock has been studied with more care than most others, and geologists are agreed, in a general way at least, as to its mode of origin.

Origin.—There is no doubt that the coal is of vegetable origin. Except by the accumulation of vegetable matter, no way is known by which such beds of carbon could be brought into existence. Furthermore, the coal and its associated shales contain abundant remains of plants, and sometimes even recognizable tree-trunks, in the form of coal, and microscopic study has revealed the remarkable fact that the coal itself, even the hardest anthracite, is often but a mass of altered, though still recognizable, vegetable tissues. Concerning the exact manner in which the beds of vegetable matter accumulated, there is some difference of opinion, and concerning the conditions under which it was converted into the various sorts of coal, there is still more.[1]

Much of the coal is essentially pure, containing little matter of any sort which was not in the plants which gave origin to it. Purity does not mean freedom from ash, since mineral matter, which on combustion becomes ash, is present in all plants.[2] Along with the large amount of coal which is pure, or nearly so, there is much which contains some admixture of earthy matter. Where the admixture of earthy matter is small, the coal may still be used; but from poor coal of this sort, there are all gradations into carbonaceous shale, the percentage of carbon becoming so low as to show itself only in a black color. Black shales are common associates of coal-beds.

The purity of many coal-beds, not only locally but over great areas, seems to warrant the conclusion that such beds were made of vegetation which grew where the coal now is. The vegetation concerned was land or swamp vegetation. Had it been washed down from the land where it grew into the situations where the coal is, and apparently there is no other way in which it could have been drifted together, it should have been mixed with earthy sediment, and the product, even where the vegetable matter had undergone the necessary changes, would have been very unlike the purer coal-beds now known. Furthermore, the nearly uniform thickness of many of the coal-beds over great areas, sometimes many thousand square miles, constitutes a strong objection to the hypothesis that it was drifted together by any process whatsoever.

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[1] Discussions concerning the origin of coal are to be found in many of the geological reports of the States where coal occurs, notably Ohio, Pennsylvania, Illinois, Iowa, Missouri, and Arkansas.

[2] Many of the modern allies of the coal-plants contain as much as five per cent of ash, and some as much as twenty.

In support of the theory that the vegetation grew where the coal-beds now are, many facts, in addition to the purity and the uniformity of thickness already cited, may be noted. Thus (1) beneath each coal-bed there is, as a rule, a layer of clay often filled with roots in the position of growth. The clay seems to have been the soil in which the coal vegetation was rooted in the earliest stages of the accumulation. (2) In association with the coal-beds, the stumps of trees are sometimes found still standing as they grew (Fig. 252). (3) In the coal-beds, or in the associated layers of shale, imprints of the fronds of ferns are found. They are often so numerous and their forms so perfect as to indicate that they were buried where they fell, rather than

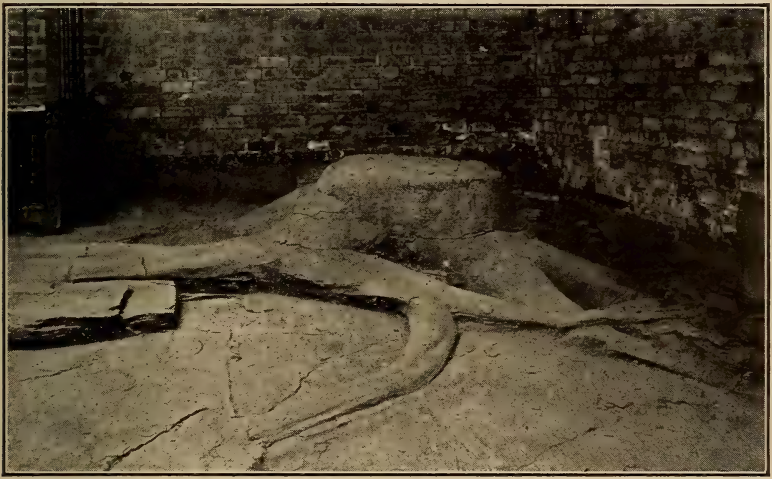

Fig. 252.—Showing a stump standing as it grew in Coal Measures near Glasgow, Scotland.

that they were drifted by moving waters from one place to another. (4) The layer of rock next overlying a coal-bed often contains abundant remains of vegetation, especially in its lower part, as if the conditions which brought about its deposition resulted in the destruction of the forest growths which had preceded. In such situations, trunks of trees 50 and 60 feet long, and 2 or 3 feet in diameter, are sometimes found. (5) The vegetable matter in and about coal-beds is made up of the trunks, small stems, leaves, and fruits of the various plants concerned, intermingled in such manner as to indicate that the vegetation grew where the coal now is. The drifting together of vegetation, while it would not have completely separated these various constituents one from another, could scarcely have left them commingled as they are now found.[1]

While it is confidently believed that most of the workable coal represents the growth of vegetation *in situ*, it is not to be understood that coal was never formed from vegetation which drifted together, or that "drifted" vegetation never entered into the formation of coal. In some of the small coal-basins of France, much vegetation washed down from the land is said to have entered into the coal,[2] and the same may be true elsewhere.

We have now to inquire in more detail concerning the conditions under which the coal-beds were formed. The things to be accounted for are three: (1) The conditions under which the necessary bodies of vegetation accumulated, often essentially free from the admixture of sediment; (2) how it was kept from decay; and (3) how it was changed into coal.

Swamps and marshes are the only places where vegetal matter is now accumulating in quantity, with little admixture of sediment. Where swamps are large, or where their surroundings are sufficiently low to prevent the inwash of sediment, vegetation is accumulating, uncontaminated with any notable amount of sand or mud. In the marshes along some parts of the Atlantic coast, for example (Fig. 253), there are great quantities of vegetal matter which is locally mixed with little sediment. Likewise in Dismal Swamp, vegetable matter, essentially free from sediment, and composed of the trunks, branches, leaves, and fruits of the trees, shrubs, and herbs which grow there, has been long accumulating, and its mass is now great. In various cypress swamps, too, great thicknesses of vegetable matter are found, essentially free from foreign matter. The same is true of mangrove swamps, which differ from the cypress swamps in that they spread into salt water. The multitude of marshes and peat-bogs in the United States and Canada are further illustrations of the accumulation of vegetable matter, sometimes mixed with abundant sediment and sometimes nearly free from it.

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[1] For expositions of the theory that the coal-plants grew where the coal is found see Logan, Trans. Geol. Soc., VI, 1842, p. 495; Newberry, Am. Jour. Sci., XXIII 1857, p. 212, and Geol. of Ohio, Vol. II, p. 125.

[2] Geikie, Text-book of Geology, 3d ed., p. 808.

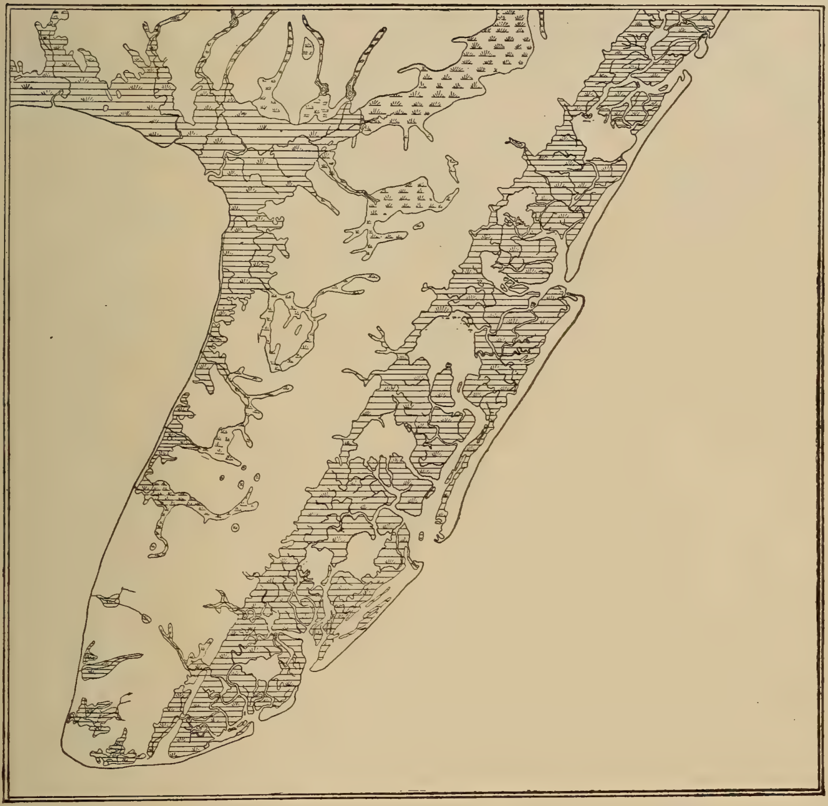

FIG. 253.—Map of the Cape May peninsula, showing coastal marshes. The unshaded areas inside the coast line are dry land.

The vegetation in such situations need not be more luxuriant than on moist lands which are not swampy. On fertile prairies and in great forests the annual growth of vegetation is great; but as the leaves, fruits, twigs, and trunks fall, they decay, and the larger part of their substance is returned to the atmosphere. If the decay of vegetation does not keep pace with its growth and death, an undecayed or partially decayed residuum of organic matter remains, giving the soil a black color. It is a matter of common knowledge that black soils are more common in moist regions than in dry ones, in cool regions than in warm ones, and on flat surfaces than on sloping ones. In a moist region there is more growth (and therefore more death) of vegetation than in a dry one, and a better chance that decay will not keep pace with death. Decay is less rapid in a cool climate than in a hot one, so the former is more likely to have a residuum of partially decayed organic matter. From a flat surface the undecayed organic matter is less likely to be removed by erosion than from a sloping one, and the poorer drainage has the effect of greater moisture. Forests, by shading the ground and checking the drainage, have the effect of additional moisture.

An increasing blackness of the soil may often be observed as the borders of a marsh are approached. The increase in blackness means an increase in the amount of undecayed or but partially decayed organic matter, and this in turn appears to be immediately connected with the increasing moisture of such situations. In the marshes themselves, where the vegetation falls into water, it usually undergoes a slow decay only, and not that type of decay suffered by the vegetation which falls on drier lands. The preserving influence of water is seen in many ways. Posts and piles set partly in water, and partly above, decay just above the water-level, while the portions below remain sound. It is the preservation of organic matter in the water of marshes and very shallow lakes which converts them into peat-bogs, for the peat is nothing more than accumulated vegetable matter undergoing those changes to which vegetable matter in water is subject.

If the surroundings of a marsh be low, little sediment is washed into it, and there is every gradation from the earthy soil about it, merely colored by organic matter, to the deposit in the marsh itself, made chiefly of organic matter. Given continued favorable conditions, and the organic matter of a bog may become very deep, as it now is in Dismal Swamp, and in many other less well-known swamps and bogs. In and about marshes and swamps we therefore find the conditions for the accumulation of considerable thicknesses of vegetable matter, essentially free from sediment, and at the same time the conditions which keep it from decay.

But while the vegetable matter is not destroyed, it is not preserved intact. The composition of wood and peat are illustrated by the following analyses (the ash is omitted), though it is not to be understood that either wood or peat has a constant composition. The difference, it will be seen, is not great.

	Carbon.	Hydrogen.	Oxygen.	Nitrogen.
Wood	49.66	6.21	43.03	1.10
Peat	59.50	5.50	33.00	2.00

The relative atomic proportions of carbon, hydrogen, and oxygen in wood are approximately expressed by the formula $C_6H_9O_4$. In the air, the carbon and the hydrogen of the wood unite with the oxygen of the air or of the wood itself, forming carbon dioxide and water, the principal products of the decay of vegetable matter. But under water, the atmospheric oxygen is largely excluded, and the elements of the wood unite with one another to a larger extent, while the oxygen of the air plays but a subordinate part. One of the common products of decay under such circumstances is CH_4 (marsh-gas), which bubbles up from many swamps and escapes into the atmosphere. The formation of this gas, as its composition shows, exhausts the hydrogen four times as rapidly as the carbon. If the carbon of the wood unites with the oxygen of the wood, forming carbon dioxide, the oxygen is exhausted twice as rapidly as the carbon. If the hydrogen and the oxygen of the wood combine, the result is to increase still more rapidly the percentage of carbon remaining, so that in whatever way these elements combine, the result must always be to increase the proportion of carbon remaining in the solid. Even under water it is probable that atmospheric oxygen dissolved in the water takes part in the changes, and in so far as this is the case, the proportion of carbon remaining after the changes have taken place is diminished.

While the exact quantitative relations of the reactions which take place are not known, and are probably not constant, the following table[1] suggests certain changes which might take place, and also the products which would remain at certain stages of the process:

Wood[2] (timber). . . . $C_{36}H_{54}O_{24}=6(C_6H_9O_4)$

$$\text{Subtract}\left\{\begin{array}{l}8CO_2\\4CH_4\\6H_2O\end{array}\right\} = C_{12}H_{28}O_{22}$$

And there remains $C_{24}H_{26}O_2$ = about the composition of brown coal.

Wood . . . . $C_{36}H_{54}O_{24}$

$$\text{Subtract}\left\{\begin{array}{l}6CO_2\\4CH_4\\10H_2O\end{array}\right\} = C_{10}H_{36}O_{22}$$

And there remains $C_{26}H_{18}O_2$, which falls within the range of bituminous coal.

Wood. . . . . $C_{36}H_{54}O_{24}$

$$\text{Subtract}\left\{\begin{array}{l}6CO_2\\6CH_4\\11H_2O\end{array}\right\} = C_{12}H_{46}O_{23}$$

And there remains $C_{24}H_8O$, which falls within the range of anthracite.

Since the changes above are changes which take place in peat-bogs, the altered vegetation there found appears to be a step on the way from the ordinary forms of vegetable tissue to coal. The following table[3] shows the composition of wood, peat, and various types of coal. From a comparison of this table with the preceding, it is not difficult to understand how vegetable matter is converted into coal

	Carbon.	Hydrogen.	Oxygen.	Nitrogen.
1. Wood.	49.66	6.21	43.03	1.10
2. Peat.	59.5	5.5	33.0	2.0
3. Brown coal.	68.7	5.5	25.0	0.8
4. Bituminous coal. .	81.2	5.5	12.5	0.8
5. Anthracite.	95.0	2.5	2.5	0.0

If the vegetable matter, after having been accumulated to great depths and after having been partially altered, say to the condition of peat, were buried beneath beds of mud or sand, it would undergo further changes, both chemical and physical, tending to bring it nearer and nearer to the condition of coal. The oxygen of the air would then be more effectually excluded, and the chemical changes more largely confined to the constituent elements of the vegetable matter. The weight of the sediment would compress the vegetable tissues, and it is believed that the result would be its ultimate conversion into coal. The various grades of coal, bituminous, anthracite, etc., are thought to represent different stages in the process of change.

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[1] After Le Conte, Elements of Geology.

[2] The composition of cellulose is usually given as $C_6H_{10}O_5$ or some multiple of this The changes can be developed equally well from this formula.

[3] Le Conte, op. cit.

If the coal-beds represent the Carboniferous swamps, as they are believed to, we have still to inquire into the conditions under which swamps as extensive as the coal-beds existed, and to seek the explanation of their frequent recurrence (one for each coal-bed) in many regions.

The first condition for a swamp is lack of drainage, and the second a sufficient, but not an excessive amount of water. Enough to stop the growth of vegetation would be excessive, and too little to preserve it from ready decay after its growth and death, would be insufficient.

In the course of the widespread, but for the most part very gentle, movements which affected the eastern interior at the close of the Mississippian period, great areas appear to have emerged from the sea. Early in the Pennsylvanian period, considerable tracts which were not submerged stood so low as to be ill-drained or undrained, and constituted marshes. The conditions of climate and moisture appear to have been such as to allow the abundant growth of vegetation in the marshes. On falling into the shallow water, or upon the water-soaked bottom, the vegetable matter underwent changes of the nature indicated above. The ill-drained areas were thus converted into peat bogs, in which, in many places, little inorganic matter was mixed with the organic. The longer the life of the bog, the deeper the peat became. The rate of accumulation, though depending on climate and on the abundance of vegetation, is always slow. Under very favorable conditions, a foot of peat may accumulate in ten years or even less, but the usual rate is probably much slower. Peat bogs are now in existence in which the depth of the accumulated organic matter is 40 or 50 feet, but the length of time involved in the accumulation is not known.

Some of the great swamps probably came into existence along the sea-shores, and some in shallow basins or undrained areas remote from the sea, for fresh-water shells are found in association with some coal-beds, and marine fossils in association with others.

The history of a coal-bed.—Each coal-bed represents the accumulated vegetable growth of a long period. It would appear that the growth and accumulation of vegetation was often brought to an end by subsidence which let the water (sea or lake or aggrading stream) in over the marshes, drowning the plants, and burying the organic matter which had already accumulated, under deposits of mud, sand, or shells which the submergence brought in its train. A second coal-bed in the same region points to the recurrence of swamp conditions, and means either (*a*) that after submergence and burial of the organic matter, slight emergence ensued, caused by land or water movement, thus reproducing the conditions for bogs; or (*b*) that by sedimentation the sea or lake bottom where the first bog had been, was built up to the water-level, restoring swamp conditions. On the former hypothesis (*a*), two successive coal-beds would represent the following sequence of events: (1) A more or less static condition with the surface ill-drained, during which the vegetable matter accumulated; (2) a subsidence of the land or a rise of the water during which the vegetable matter was buried by sediment; (3) a reverse change, bringing the surface again to the condition which it occupied in the first place; (4) a later submergence, effecting the burial of the later growth of vegetation. On the second hypothesis mentioned above (*b*), but one movement is demanded. Stages (1) and (2) would have been as above, but the sedimentation of (2) continued until the swampy condition of the region was reproduced as a result of aggradation. The burial of the vegetation calls for further submergence. In other words, the first hypothesis calls for oscillation of level; the second, for successive movements of one phase only.

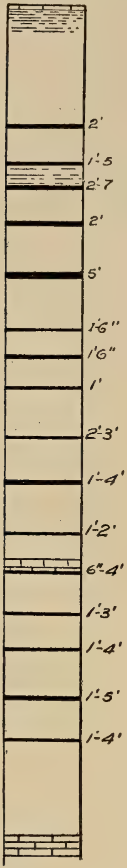

Fig. 254. — Generalized section of the Coal Measures in Kentucky. Total thickness about 800 feet. The heavy black lines = coal. (Norwood, U. S. Geol. Surv.)

The number of coal-beds is often great. In Pennsylvania it frequently (but not everywhere) exceeds 20; in Alabama, 35 (not all workable) have been enumerated; in Nova Scotia, the number, including some dirt-beds, is said to be about 80; but in the Mississippi basin west of the Appalachians, the number is often less than a dozen (Figs. 254 to 257). Thus in Illinois the number of workable beds is nine.[1]

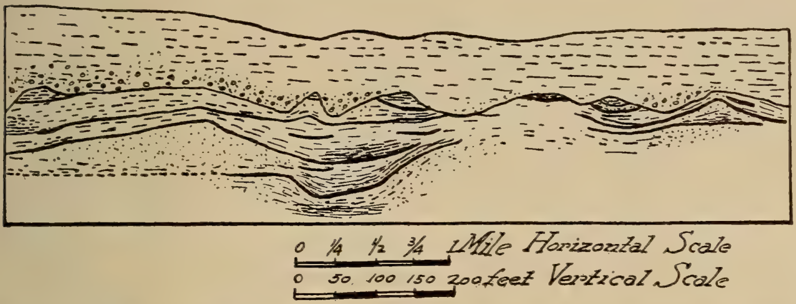
0 1/4 1/2 3/4 1 Mile Horizontal Scale
0 50 100 150 200 feet Vertical Scale

Fig. 255.—Section showing coal beds (heavy black lines) in Bay County, Mich., Amelith shaft. (Lane, U. S. Geol. Surv.)

If the foregoing sequence of events was repeated for each coal-bed, it is manifest that the surface of great areas of the continent or else the surface of the sea, was in an unstable attitude during the Carboniferous period. The second hypothesis (*b*) has the merit (so far as it is a merit) of greater simplicity than the first, but is probably not applicable to all cases. The fact that local unconformities abound in the Coal Measures (Ind., Ill., Ia., *et al*, Figs. 258 to 260) shows that the surface was locally out of water and subject to erosion at various times and places in the course of the period. This points to changes in the relative level of land and water (partly the sea and partly land waters), though it does not show which was the changeable element. When it is remembered that many relative changes of level may have taken place without giving origin to coal seams, it is not too much to say that the number of fluctuations in the relative level of land

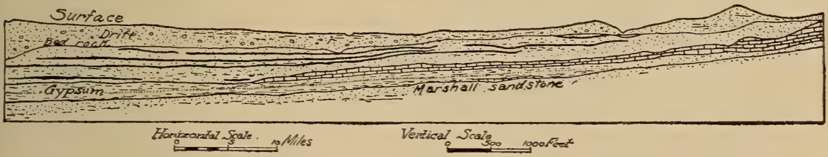

Fig. 256.—Section showing coal belt (heavy black lines) along the Pere Marquette Ry., Mich., east from Alma. (Lane, U. S. Geol. Surv.)

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[1] Reports on coal have been published by all States containing coal, where there have been surveys. For local details see reports of Pennsylvania, Ohio, Kentucky, Tennessee, Alabama, Indiana, Illinois, Iowa, Missouri, Arkansas, Kansas, and Texas.

and water in the eastern part of North America during the Pennsylvanian period, was great, though perhaps not greater than during other periods.

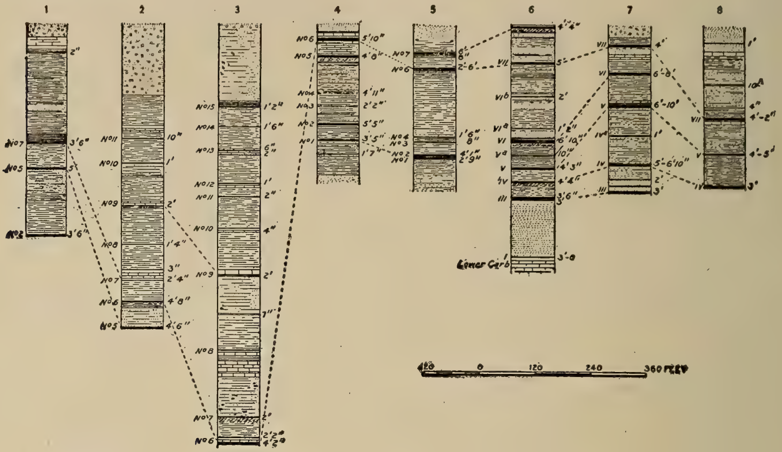

Fig. 257.—Sections of Illinois and Indiana Coal Measures; 1, shaft at Oglesby, La Salle Co., Ill.; 2, air shaft at Decatur, Macon Co., Ill.; 3, shaft at Kinmundy, Marion Co., Ill.; 4, boring at Galum Creek, Perry Co., Ill.; 5, boring at Danville, Vermilion Co., Ill.; 6, connected section from South Vermilion and Parke Cos. Ind.; 7, connected section from Dugger and Linton, Sullivan and Parke Cos., Ind.; 8, connected section from Henderson, Ky., and Evansville, Ind. (Ashley, U. S. Geol. Surv.)

Extent and relations of coal-beds.—The widespread distribution of coal does not mean that any one marsh necessarily covered the whole of any one great coal-field. Some of the coal-beds, however, are known to be of great extent. Thus a single bed, the Pittsburg, is known to be workable over an area of some 6000 square miles[1] in

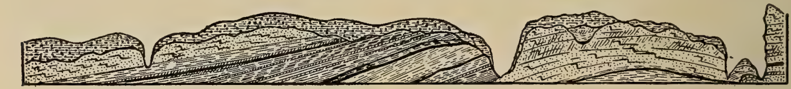

Fig. 258.—Local unconformity in Coal Measures of central Iowa. (Keyes, Ia. Geol. Surv.)

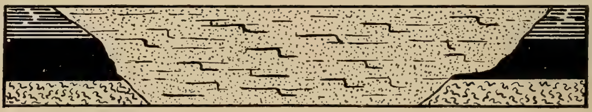

Fig. 259.—Local unconformity in the Coal Measures; sandstone occupying "cut out" in coal beds. Smoky Hollow mine, Marion Co., Ia. (Keyes, Ia. Geol. Surv.)

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[1] White, West Virginia, Geol. Surv., Vol. II, p. 166.

western Pennsylvania, Ohio, and West Virginia, and to have at least an equal extent where too poor to be generally worked. Many coal beds, on the other hand, do not occupy great areas. From their thicker portions they thin out in all directions, often grading into black shale. From these facts it is inferred that within the general area of a coal-field there may have been islands and peninsulas above the marsh level. Such areas interrupted the continuity of the swamps then, and interrupt the continuity of the coal-beds now.

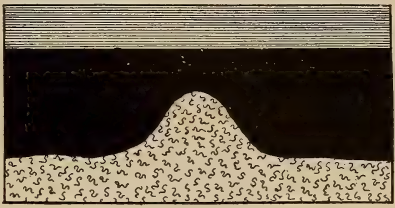

Fig. 260.—Irregularity in a coal bed showing a "horseback" in Craig Slope, Kalo, Ia. (Keyes, Ia. Geol. Surv.)

No parallelism between the coal-beds of different fields has been made out, and is not likely to be. Even within the same field the parallelism is by no means perfect, as shown by the fact that more seams are found in some parts of a field than in others. On the other hand, the larger coal-beds are often continuous over great areas, as already noted in the case of the Pittsburg bed.

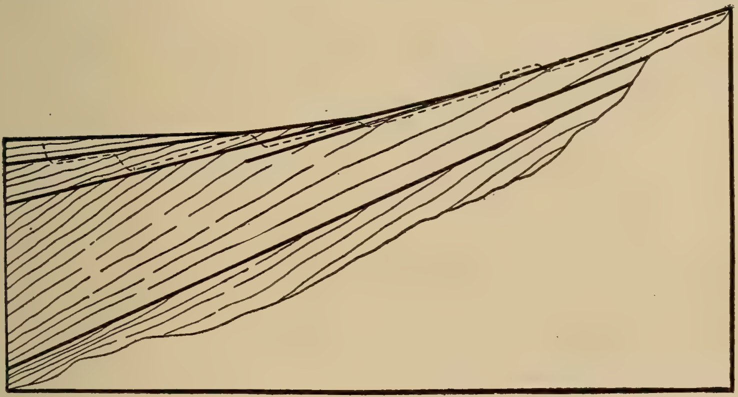

Fig. 261.—Bifurcation of a coal bed. The heavy black lines = coal. (Winslow.)

Traced laterally, a bed of coal is sometimes found to divide (Fig. 261) or, traced in the opposite direction, two beds are sometimes found to unite.[1] Fig. 262 suggests a possible sequence of events by which the bifurcation may be brought about. Vegetable matter for a coal seam is accumulating along *a-b* (*A*). The outer part of the bog then sinks (*B*) so that sediment is deposited over a part of the area (*a* to *c*) where vegetation formerly grew. When the depressed area (*a* to *c*) is aggraded or elevated (relatively) sufficiently (*C*), the bog is restored at the left, and the two layers of organic matter at the left, unite at the right, where the accumulation of vegetable matter has not been interrupted. It will be readily seen that other sequences of events might bring about the same result, and that, if this process is frequently repeated, great differences might exist in the number of coal seams in different parts of the same general region.

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[1] The Nature of Coal Horizons; see Winslow, Geol. Surv. of Missouri, Preliminary Report on Coal, p. 25. Also Keyes, Jour. Geol., II, 178.

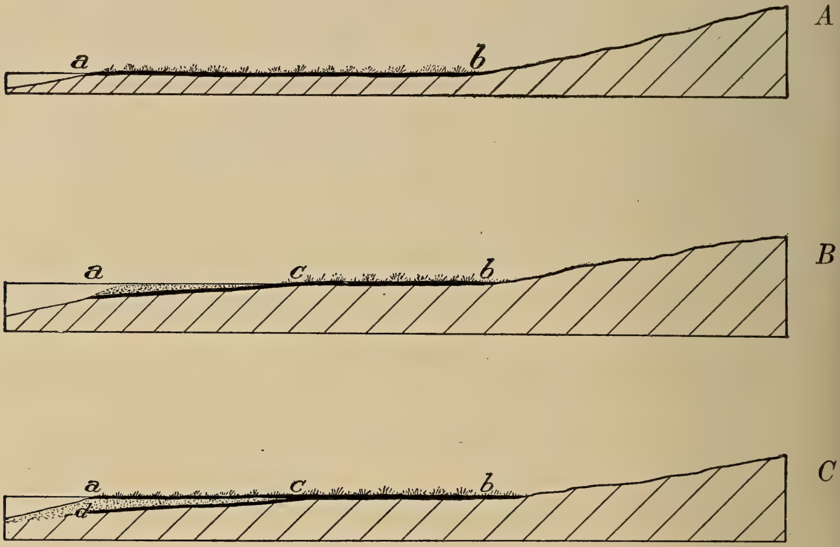

FIG. 262.—Diagram illustrating the sequence of events which might lead to the bifurcation of a coal bed. In the first diagram, vegetal matter is accumulating from *a* to *b*; in the second, a part of the area, *a* to *c*, is represented as submerged; in the third, the tract from *a* to *c* has been built up or lifted up (relatively) so as to become a marsh again, and vegetal matter is accumulating from *a* to *b*.

Varieties of coal.—The exact manner in which the different varieties of coal have arisen has never been satisfactorily determined. In general it is true that the anthracite coal occurs in mountainous regions, where the coal and other layers of rock with which it is associated have been subject to more or less intense dynamic action. Thus, in the mountains of eastern Pennsylvania (Fig. 263) the coal is mainly anthracite (Figs. 264–267), while in the central, and in most of the western coal-fields of Pennsylvanian age, where the strata are nearly horizontal or but slightly deformed (Figs. 255, 256 and 267 to 271), and altogether non-metamorphic, the coal is bituminous or soft. In Arkansas[1] where the strata have been subject to some, but not to extreme dynamic action, there is coal which is semi-anthracitic. Where the metamorphism of the associated rock has been extensive, the coal has gone beyond the anthracitic stage and has become graphitic.

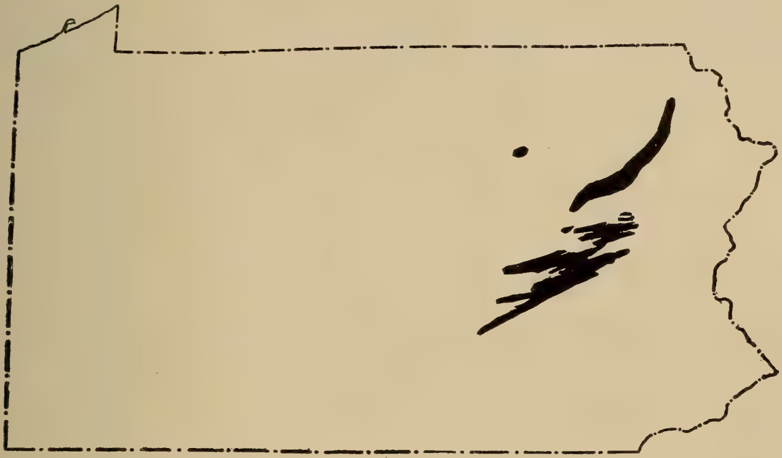

Fig. 263.—Map showing the areas of anthracite coal in Pennsylvania.

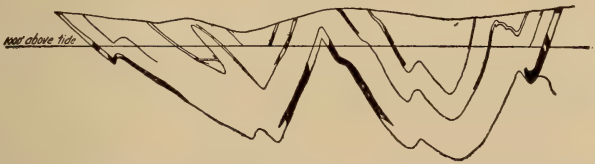

Fig. 264.—Section across Panther Creek basin in the anthracite region of Pennsylvania, showing the position of the strata and the coal beds. (Stoek, U. S. Geol Surv.)

Thus in Rhode Island, where the strata have been highly metamorphosed, the coal is highly anthracitic, or even semi-graphitic.[2]

Anthracite coal is also found in some places (though not in the Coal Measures of the United States) in contact with dikes, in just the situations where other sorts of rock are metamorphosed. These phenomena long ago suggested that anthracite is to be looked upon as metamorphic coal produced from bituminous by processes similar to some of those which induce metamorphism in other sorts of rock.

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[1] Ann. Rept. Ark. Geol. Surv. 1888, Vol. III.

[2] Geology of the Narragansett Basin, Mono. XXXIII, U. S. Geol. Surv.

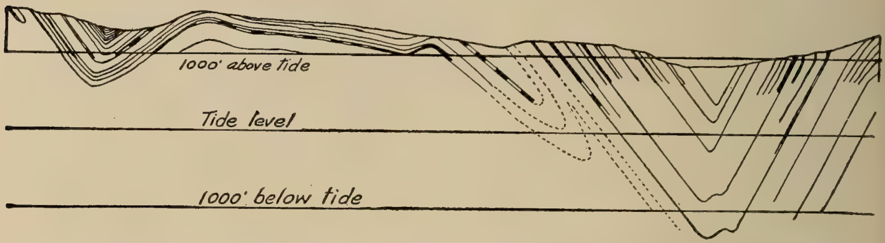


Fig. 265.—Section of the Western Middle anthracite coal basin of Pennsylvania. Length of section, a little less than two miles. (Stoek, U. S. Geol. Surv.)

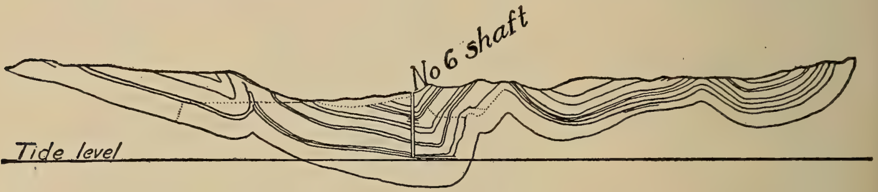


Fig. 266.—Section south of Nanticoke, showing the position and relations of the coal beds, in the Northern anthracite coal field. Length of section a little less than two miles. (Stoek, U. S. Geol. Surv.)

The fact that metamorphic coal is usually found in regions where erosion has exposed its beds (Figs. 264 to 267) has led to the conjecture that exposure may be a real factor in the problem, the exposure favoring the escape of the volatile constituents, and so aiding in the transformation of bituminous coal to anthracite. Beds of bituminous coal are, however, often exposed in valley bluffs.

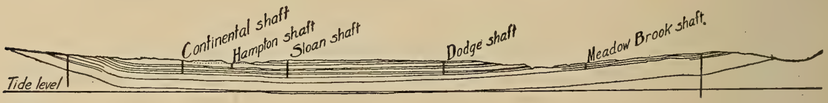


Fig. 267.—Section at Scranton. Length of section between 4 and 5 miles. (Stoek, U. S. Geol. Surv.)

Both dynamic action, involving pressure and heat, and exposure would seem to be conditions favoring the development of anthracite, but it does not follow that these are the only factors in the problem, or that anthracite coal has never been produced in other ways. It

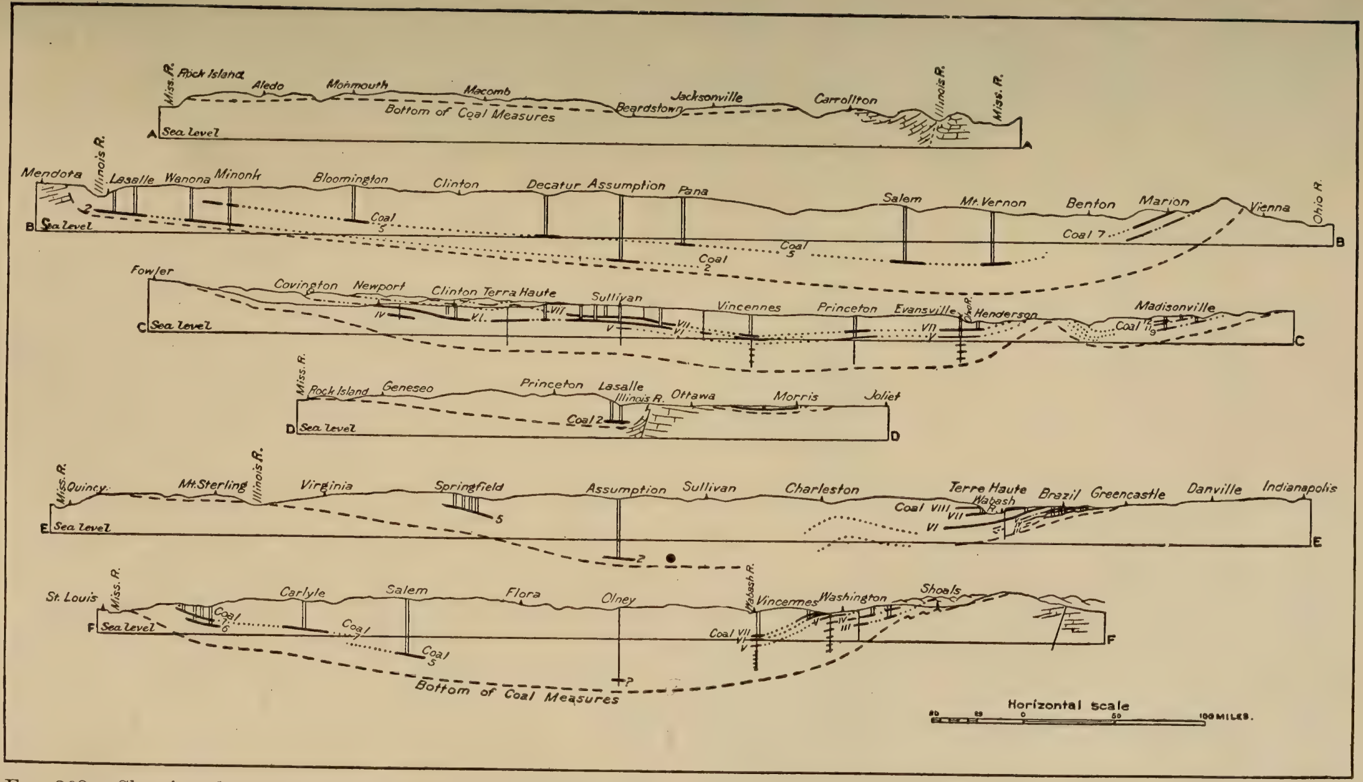


FIG. 268.—Showing the general structure of the Coal Measures in Indiana and Illinois. The names which appear on the sections show their location. (Ashley, U. S. Geol. Surv.)

has been suggested that the anthracitic character of coal depends on the length of time the vegetation was exposed before being buried by other sedimentary rocks.[1] This seems to demand that thick beds of coal be more anthracitic at their bases than at their tops, or else that the thin, slowly accumulated parts be more anthracitic than the thick, faster-formed parts. Neither of these things seems to be generally true, though the lower part of a coal-bed is sometimes "harder" than the upper.

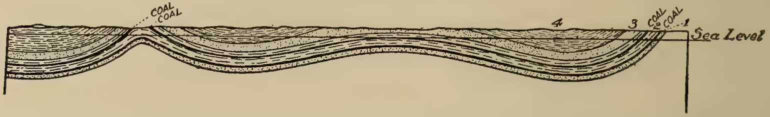
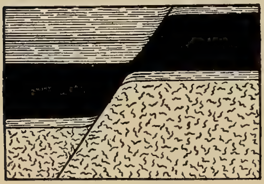


FIG. 269.—Section showing positions and relations of the coal beds at a point in Indian Territory. The black lines indicate coal beds. Length of section about 11 miles. (Taff, U. S. Geol. Surv.)



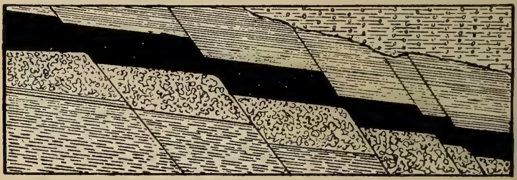


FIG. 270. FIG. 271.

FIG. 270.—Diagram showing slight faulting in the coal beds of Iowa. Bloomfield shaft, Des Moines, Ia. (Ia. Geol. Surv.)

FIG. 271.—Step fault in Davidson mine, Jasper Co., Ia. (Ia. Geol. Surv.)

Other varieties of coal appear to depend on the conditions to which the vegetable matter was subject, either before or after burial, and on the degree to which the bituminizing process has been carried.

Iron Ore.

The iron ore of the Coal Measures occurs in layers like the coal, or in the form of nodules which are often concentrated at a given horizon, forming a nearly continuous layer. The ore is sometimes in the form of the carbonate of iron (siderite) and sometimes in the form of oxide. The iron is often associated with clay, making *clay ironstone.* The iron ore of the Coal Measures seems to have been largely deposited as a precipitate from the waters of inland and local basins, while the other members of the system were being laid down. Dissolved by the land waters from the soil and rocks, it was brought to the marshes in some soluble form. In the marshes, it was precipitated either in the form of the carbonate or ferric oxide. Subsequent oxidation has changed some of the original carbonate into ferric oxide. The principal iron ores of the Pennsylvanian system occur in Pennsylvania (Allegheny and Monongahela series) and eastern Ohio (Allegheny series).[1]

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[1] Stevenson, Jour. of Geol., Vol. I, p. 677.

General Geographic Conditions in the Eastern Interior.

Returning for a moment to the system of which the coal-beds form an inconsiderable part, it is to be noted that many of the clastic beds associated with the coal are known by their fossils to have been laid down in fresh water. Some of the occasional limestone-beds, on the other hand, as well as some of the clastic beds, were deposited where marine conditions prevailed. It follows that marine, lacustrine, and marsh conditions may also have alternated with the others, but such conditions, especially if the land be too low to suffer notable erosion, leave but indistinct records.

The succession of Pennsylvanian beds in southwestern Pennsylvania (Fig. 242) illustrates the great series of changes which took place in the sedimentation in the course of the period. These changes were probably the result of geographic changes, such as variations in the height of the land, the depth of the water, or in the areal relations of land and water, due to gradation. It is not to be inferred that changes were more frequent at this time than during other periods. Their record is conspicuous because of the coal; or, in other terms, because the land was near sea-level, so that extensive submergence and emergence resulted from slight changes of relative level of land and sea. It should be remembered that a series of equally frequent and equally extensive movements, or that equivalent degradation and aggradation, would leave no such record of themselves, if the surfaces concerned were well above or well below sea-level. It was the oscillation just above and just below water-level which allowed the record to be so clearly preserved. How far the oscillations were due to warpings of the land, and how far to changes in the level of the sea, cannot now be determined; but when we recall that the ocean-level must respond to every deformation which affects its bottom (unless compensated by an equivalent opposite movement), and to every stage of filling,[1] it does not seem strange that its level is in a nearly perpetual state of fluctuation.

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[1] For statistics concerning production of iron, see Census Reports (Vol. XV, 10th Census) and Mineral Statistics, U. S. Geol. Surv.

In general, it may be said that the movements of the crust which have been of most importance, from the point of view of continental or biological evolution, are not those which have affected high land or deep sea bottom, but those which have converted sea bottom into land, or land into sea bottom. Such changes are most likely to have taken place where land was low, or water shallow. From the point of view of geology, therefore, *the critical level of crustal oscillation is the level of the sea.*

Thickness.

The Coal Measures differ greatly in thickness in different sections of the country, but, like all the preceding formations of the Paleozoic, they are especially thick in the Appalachian mountains, measured by the usual method.

The thickness of the Millstone Grit (Pottsville conglomerate) alone ranges up to 1700 feet in Pennsylvania, but it thins rapidly to the westward. The Coal Measures are equally variable in thickness, ranging from nearly zero to more than 3000 feet (Pennsylvania to Alabama). In the interior, the corresponding formations rarely much exceed 1000 feet. In Ohio they are about 1200 feet thick; in Indiana, 1000 feet; in Illinois, 1650 feet; in Michigan 300 feet, and in Iowa, 600 feet. In Arkansas, the Coal Measures attain the remarkable thickness of more than 20,000 feet,[2] from which it is inferred that there must have been land close at hand capable of supplying sediments in great quantity, combined, probably, with conditions favorable to deposition in sloping attitudes. This was probably the axis of the Ouachita uplift. In Texas, the Pennsylvanian has a thickness ranging up to 5000 feet.[3] In the Wasatch mountains, the Carboniferous strata (including the Lower Carboniferous) have been estimated to be about 13,000 feet thick, and in Nevada, 10,000 feet. In these regions, therefore, active deposition was in progress, and so far as the sediments are clastic, they were probably derived from the land area of western Nevada. For further details as to thickness, see the preceding sections, pp. 557–562.

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[1] Salisbury. Jour. of Geol. Vol. XIII. p. 469.

[2] Cited in Report of the Dept. of Geol. and Nat. Res. of Indiana.

[3] Richardson, Bull. G., Univ. of Texas Mineral Survey.

Duration of the Coal Measures Period.

So uncertain is our knowledge of the duration of geological time that all groups of data which can be made to throw light on the subject are of interest, even though they do not lead to trustworthy numerical conclusions. A vigorous growth of vegetation has been estimated to yield annually about one ton of dried vegetable matter per acre, or 640 tons per square mile. If this annual growth of vegetable matter were all preserved for 1000 years, and compressed until its specific gravity was 1.4 (about the average for coal) it would form a layer about six inches thick. But a large part of the vegetable matter, even in peat bogs, escapes as gas (CO_2, CH_4, etc.), in the making of coal. It has been estimated that three to four fifths of it disappears in this way. The six-inch layer would then be reduced to two tenths or to one tenth of a foot, and a layer one foot in thickness would require 5000 to 10,000 years. The aggregate thickness of coal is frequently as much as 100 feet, and sometimes as much as 250 feet. At the above rate of accumulation, and with the above proportions of loss, periods ranging from 500,000 to nearly 2,500,000 years would be needed for the accumulation of such thicknesses of coal.

It should be borne in mind, however, that much depends on the rate of growth of Carboniferous vegetation, which is not known. On the other hand, these figures refer to the coal only, not to the Coal Measures. The greater part of the Coal Measures is made up of shale and sandstone, and of these formations there are thousands of feet, even where the sediments were largely fine and their accumulation therefore probably slow. It would hardly seem unreasonable to conjecture that their deposition might have consumed an amount of time equal to or even greater than that demanded by the coal. This would double the above figures, making them something like 2,000,000 and 5,000,000 years respectively. These figures must be taken to mean nothing more than that the best data now at hand indicate that the Pennsylvanian period was a very long one.

Close of the Carboniferous Period.[1]

After the long period of oscillation above and below the critical level recorded by the Coal Measures, the interior area east of the Mississippi was brought above the level of the sea, not to sink again beneath it during the Paleozoic era, and some of it at no later time. This uplift marks at once the close of the Carboniferous, and the inauguration of the Permian period. It is also probable that the deformative movements which were to result in the folding and uplift of the Appalachian mountains began at this time. Dikes of igneous rock affect the Carboniferous strata of northwestern Kentucky and southern Illinois, but the date of their intrusion has not been determined. It seems not improbable that it was during the general period of deformation which marked the close of the Paleozoic; but this is conjecture.

There were also notable changes in the western half of the continent, for the strata of the Permian period are much less widespread than those of the Carboniferous. Where they occur, their constitution and their fossils are such as to indicate not only different relations of land and water, but different conditions of erosion, and the absence of the sea from some areas where deposition was in progress. In the Sierras,[2] too, there seems to have been deformation and metamorphism of the Carboniferous beds at some time antedating the Jurassic period. The exact date of the disturbance has not been fixed, but it may have been contemporaneous with that in the Appalachian Mountain region.

In America, the Permian has usually been regarded as the closing stage of the Carboniferous. This classification seems best to fit the facts of the eastern part of the continent, but when the relations of the Permian in other parts of the world are considered, it seems more fitting to regard the Permian as a distinct period.

IN FOREIGN COUNTRIES.

Europe.

General.—As in America, the oldest formation of the Upper Carboniferous in Europe is often a conglomerate and sandstone formation, the Millstone grit, which in some parts of Britain attains a thickness of 5500 feet.[1] This formation has the same stratigraphical position, and probably the same significance as the formation of corresponding name (Pottsville, etc., see p. 539) in America.[2] It was indeed this correspondence which led to the adoption of the English name for the American formation. The thick Millstone grit of England is thought to represent a shore accumulation against a ridge of Paleozoic rock which crossed central England in the early part of the Carboniferous period. The ridge was later submerged, but not until some part of the Coal Measures had been deposited. North from this ridge the Millstone grit thins rapidly. The fossils of the Millstone grit are singular in that the plants resemble those of the Coal Measures above, while the animals are more like those of the Lower Carboniferous below.[3]

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[1] For general account of Appalachia during the Paleozoic Era see Willis, Md. Geol. Surv., Vol. IV, pp. 23–88.

[2] See description of the Gold Belt, in the late folios of the U. S. Geol. Surv.

The formations of the western European Coal Measures, like those of eastern North America, consist principally of shales (and clays), with subordinate amounts of sandstone and limestone. Associated with these commoner sorts of rock, there are beds of coal and clay-ironstone, both of which occupy positions corresponding in all essential respects, with those of the similar formations in eastern North America. As in America, there are local unconformities within the system. The system contains workable coal in Great Britain, Ireland, Belgium, France, Spain, Germany, Austria, and Russia, but the total area of productive coal in Europe is much less than in America. In places in Wales, there are as many as 100 seams of coal, many of which are worked. In Belgium, and in some parts of Germany the number of coal-beds is also very large. In Westphalia the number of workable beds is said to be 90.[4] The aggregate (maximum) thickness of the coal in Lancashire is 150 feet; in Westphalia, 274 feet; in Mons (Belgium), 250 feet. In central and northern France there are more than 300 small areas where portions of the Coal Measures are found. Some of them contain remarkable thicknesses of coal.[5] The Coal Measures of central Europe are less wide-spread than the Lower Carboniferous in the same region. Coal-beds are numerous in the Coal

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[1] Geikie, Text-book of Geology, Vol. II, p. 1047.

[2] The Millstone grit is sometimes regarded as the representative of a separate time-division coördinate with the Lower and Upper Carboniferous.

[3] Geikie, p. 1054.

[4] Idem, p. 1047.

[5] Idem, p. 1053.

Measures of Silesia, one bed attaining a thickness of 50 feet.[1] Here, as elsewhere, beds of marine origin alternate with those which were deposited on land, in marshes, etc. The constitution of the system is such as to show that physical conditions corresponding to those of the Pennsylvanian period in eastern North America were widespread in western Europe.

It will be remembered that the coal-bearing part of the Carboniferous series in America is confined to the eastern half of the continent. The chief areas of productive Coal Measures in Europe are in the western part of the continent, another of the many rather striking correspondences between the formations in those parts of these continents which border the same ocean. Fig. 272 shows the distribution of coal in Great Britain, and 272*a*, in the Lower Rhine basin. In

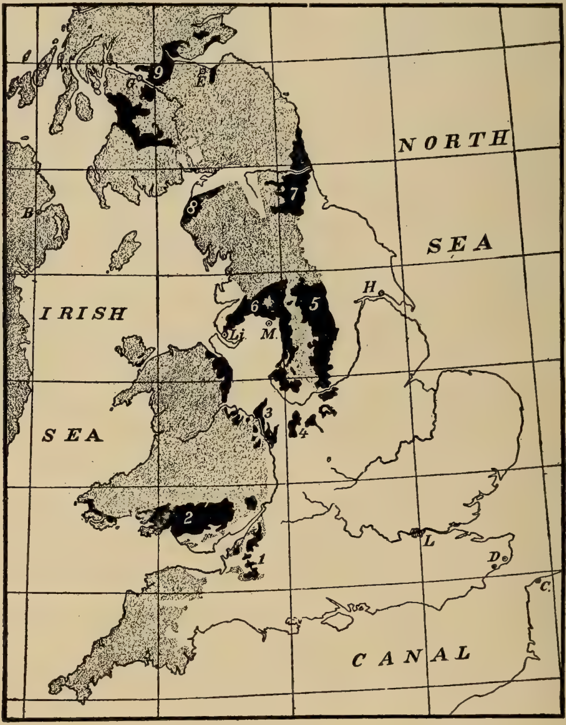

Fig. 272.—Sketch map showing distribution of coal in Great Britain (Kayser).

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[1] Idem, p. 1054.

southern Europe, the Lower and Upper Carboniferous are less distinctly separated.

In Russia, the two types of Carboniferous formations, the marine and the non-marine, are found, but not in the same relations as in the western part of the continent. Instead of the marine type below, and the lake-marsh-lagoon type above, the order seems to be so far reversed that the Lower Carboniferous contains most of the coal, while the Upper is made up chiefly of limestone. There is however much marine limestone in the Lower Carboniferous, and in southern Russia (Donetz coal-field) some coal in the Upper. The Upper Carboniferous limestone of Russia (Fusulina limestone) is represented by similar formations in southern Europe, where the system is more like that of eastern than that of western Europe. The faunas of the marine system in southern Europe, and of the marine part of the system in eastern Europe have much likeness to those of western North America, suggesting that marine life was able to pass between these continents, via northern Asia.

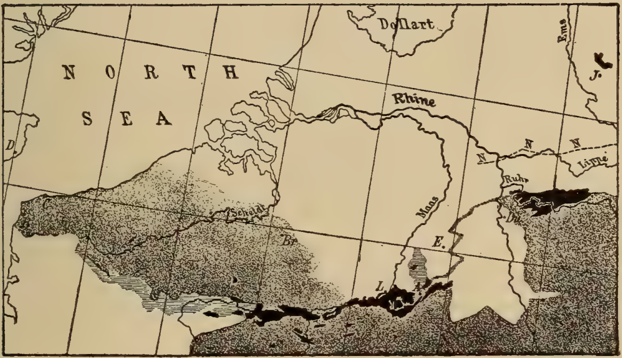

FIG. 272*a*.—Sketch map showing the position of the Carboniferous coal beds (black areas) in the lower Rhine basin (Kayser.)

The upper part of the Coal Measures system of Europe at various points and at various horizons contains bowlders, sometimes of large size, and beds of breccia or conglomerate of sub-angular fragments. The bowlders are of granite, gneiss, schist, quartzite, etc., and occur sometimes singly, and sometimes in groups. They have often been thought to represent deposits made by icebergs, and so to point to the existence of glaciers;[1] but this interpretation cannot be looked upon as established. Other interpretations, such as the transportation of bowlders by uprooted trees floated out to sea, are tenable.

Though the Coal Measures are widely distributed on the continent, the areas where they are exposed are relatively small, as compared with those of America. It is not in all cases possible to say whether the detached areas are the dissevered remnants of areas which were once extensive, or whether they are but parts of areas which are still continuous, though largely buried by younger beds. The system appears at the surface in relatively large areas in Belgium and northern France, and in small areas in southern France, and the Iberian peninsula. It is also known at many points in the mountain regions of central Europe, and has great development in Russia.

North of the European continent, the Carboniferous formations (Fusulina limestone, Coral limestone, etc.) are represented in some of the Arctic islands (Spitzbergen, Nova Zemla, Bear Island).

Thickness.—The Coal Measures of Europe attain great thickness, being 8000 feet (13,500 including the Millstone grit) thick in Lancashire, and several thousand feet in many parts of Great Britain and Ireland. These extraordinary thicknesses of sedimentary rock in Great Britain must mean the presence close at hand of somewhat extensive and high land areas.[2] The corresponding strata attain a thickness of 10,000 feet in western Germany, where they contain much coal.

Igneous rocks and crustal disturbances.—The granites of the Harz, Thüringerwald, Black Forest, Vosges, and other mountains of central Europe, appear to date from the end of the Early Carboniferous, though the eruptions probably continued into the Later Carboniferous. Various sorts of igneous rocks are associated with Upper Carboniferous formations of sedimentary origin in Brittany, Scotland, some parts of England (Cornwall), and Scandinavia (near Christiana).

The extrusion of these igneous rocks seems to have been an accompaniment of the crustal disturbances which were in progress during the period. In middle and western Europe, these disturbances began at the close of the Early Carboniferous, as already noted (p. 516), and continued through the Permian. The truncated remnants of the western part (Ireland to central France) of the central European Paleozoic Alps formed at this time, have been called the Armorican mountains,[1] while the eastern part (southern France to northern Bohemia and perhaps beyond), has been called the Variscan Alps. Some of the stubs of these old mountains have been uplifted (relatively) in later times.

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[1] Ramsay, Quar. Jour. Geol. Soc., 1855, p. 185.

[2] Geikie, Text-book of Geology, 4th ed. p. 1047.

The Carboniferous rocks of some parts of Europe have been much deformed. In Mons (Belgium) a shaft 1050 feet deep passes through the same bed of coal six times. At Liége in Belgium, and in the Boulonnais (France), workable coal has been reached after penetrating the inverted Devonian beds.[2] While these are extreme cases, deformation of a less pronounced type is widespread in western Europe, and not unknown elsewhere. Figs. 273 and 204 represent the complicated structure of the system at the localities indicated, and Fig. 274 shows the remarkable subdivisions or branchings of a thick coal-bed.

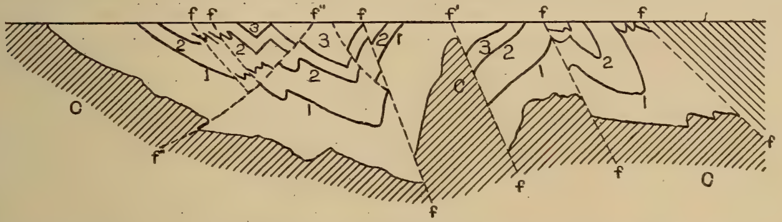

Fig. 273.—Sketch of the Liége coal basin. D = Devonian; C = Carboniferous; 1, 2, 3 = beds of coal; f, f, etc. = faults. (Vancherpenzeel-Thim.)

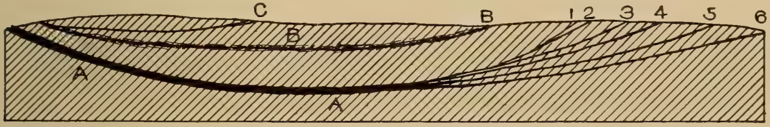

Fig. 274.—Vertical section showing the general disposition and branching of beds of coal (heavy lines) at Commentry. (Fayol.)

Other Continents.

Asia.—The Upper Carboniferous of Asia is represented by both marine and non-marine formations. The latter are often rich in coal. The marine phase is found in eastern Turkestan, at the mouth of the Lena, in some of the mountains of Siberia, in western and northwestern China, at Vladivostock, in eastern Japan, in Kiangsi in southern China,[1] and in Sumatra. The non-marine phase is found in Heraclea in Asia Minor, and on the east side of the Middle Urals, where it contains salt and gypsum, and in various parts of China.

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[1] Suess, Antlitz der Erde, Vol. II, 1888, p. 42.

[2] Geikie, op. cit., p. 1053.

In China,[2] three general divisions of the Carboniferous have been recognized. The lowest corresponds, in a general way at least, with the lower division of the Carboniferous limestone of Europe (Mississippian of America); the second is the coal-bearing division, containing much bituminous and anthracite coal; while the third is marine, consisting of the usual phases of sedimentary rocks, and seeming to correspond with the Upper Carboniferous limestone of Russia and southern Europe, and with part of the Carboniferous limestone of western North America. The Carboniferous of some parts of China, especially in the province of Shansi, is said to contain coal-beds which surpass any found elsewhere in the whole world. In the province cf Shansi there is said to be a coal-field, 35,000 square kilometers in extent, where the horizontal beds of anthracite reach a thickness of 10 meters. In the southwestern part of China there are also great beds of bituminous coal.[3] The Carboniferous system is also present in India.[4]

Africa.[5]—The Carboniferous formations of northern Africa correspond in a general way with those of southern Europe. They are generally of marine origin, so far as now known, and without coal. In southeastern Africa, a single Carboniferous coal basin has been reported near Teté in Zambesi.[6] Upper Carboniferous rocks are also reported from parts of Sahara and Egypt.

Australia and New Zealand.—The Carboniferous (Permo-Carboniferous) system is well developed in eastern Australia and in Queensland. Here, as already noted, the Lower Carboniferous consists of marine sedimentary beds, often much disturbed and metamorphosed, and associated with igneous rock. Above the Lower Carboniferous lies the Upper or Permo-Carboniferous system, which contains coal, and which attains the remarkable thickness of something like 11,000 feet. The system is remarkable because of its singular conglomerates, some of which are of glacial origin. These will be referred to again in connection with the Permian.

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[1] Kayser, Formationskunde, p. 203.

[2] Richthofen, China.

[3] Kayser, Formationskunde, p. 205. Citing Richthofen, China, Vol. II, p.473.

[4] Oldham, Geology of India, 2d ed., 1893.

[5] Kayser and Geikie, op. cit.

[6] Kayser, Geologische Formationskunde, p. 207.

South and Central America.—In South America, rocks of Late (Upper) Carboniferous age are somewhat widely distributed, though less so than those of the Devonian period. The system has wide distribution in the lower part of the basin of the Amazon, where it rests on older formations unconformably, and is not generally coal-bearing. In Central America, the same system is reported from Guatemala.

THE LIFE OF THE PENNSYLVANIAN PERIOD.

I. The Plant Life.

With the opening of the Carboniferous period the supreme biological interest shifted from the sea to the land, and centered in the vegetation and in the amphibians, the forerunners of the great line of terrestrial vertebrates. The leading interest lay in the Coal flora, and to that we turn at once.

The Coal Flora.

The Carboniferous vegetation was climacteric in two senses, which combine to make it doubly interesting; it was climacteric in its preservation, and it constituted a real climax in plant history. The conditions that favored phenomenal preservation have already been set forth. This extraordinary preservation has with little doubt given the Coal flora a degree of prominence over the preceding and succeeding floras that it did not altogether possess, and there is perhaps need to be on guard against over-emphasis; but it was really a great period in the history of plant-life. The leading factor was the pteridophytes which at this time reached their widest deployment, and the summit level of their organization. Ancestral gymnosperms were present, but they held a secondary though not unimportant place. The angiosperms, the present ruling type, had not yet appeared. The lower groups are but feebly represented in the record. It is not certain that there were any mosses or liverworts, though Renault, Zeiller, and others think that mosses were probably present. There are good theoretical grounds for believing that bacteria, fungi, and, in moist places, semi-terrestrial algæ were present in great abundance, but for obvious reasons their record is obscure. Regnault has identified bacteria.

It was emphatically the period of the *Pteridophytes,* and their deployment in numbers, size and grade of organization was very remarkable. There were true ferns, transitional ferns, and fern-like gymnosperms; there were horsetails in the form of calamarians, sphenophylls in typical development, and gigantic lycopods in the form of lepidodendrons and sigillarias, or, in more technical terms, there were *Filicales, Cycadofilices, Equisetales, Sphenophyllales,* and *Lycopodiales,* all the great divisions of the group, and all of these were nearly or quite at their climax, and some of them were verging into other types. An attempt is made to represent their general aspect in Fig. 275.

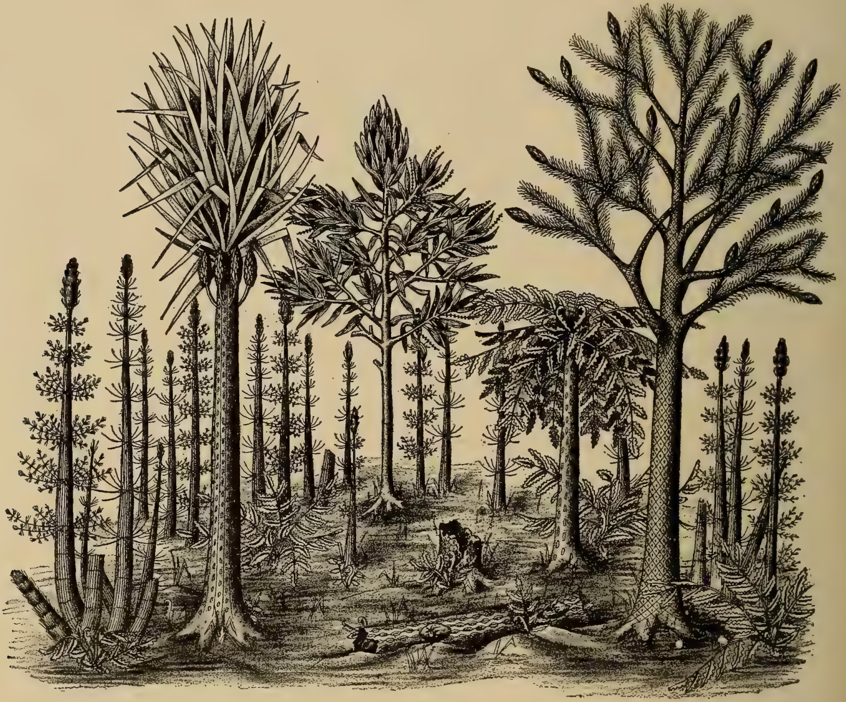

FIG. 275.—A composite group of leading Carboniferous plants adapted from restorations by various paleobotanists by Mildred Marvin. In the foreground at the right, *Lepidodendron;* at the left *Sigillaria;* in the right center rear, a tree fern; in the left center rear, *Cordaites,* at the extreme right and left, *Calamites.*

The Filicales.—Fern-like leaves surpassed all other fossil forms in number, but it is now known that many, perhaps even a majority, of these belonged to the transition group, *Cycadofilices*. True ferns were present and apparently abundant, but precisely how abundant is yet undetermined. The ferns were a strangely persistent type, like the brachiopods in the sea. At their first appearance in the record, they had already the distinctive forms of existing ferns (Figs. 275, 276, *a–c*, and 277). Later they played a notable part in the floras of many periods, and they are yet an appreciable feature in the plant world. Ferns may be found to-day that might, so far as outer form is concerned, be referred to genera prevalent in Carboniferous time; yet under this general similarity and persistency of form, they have undergone notable changes of structure and function. In Car-

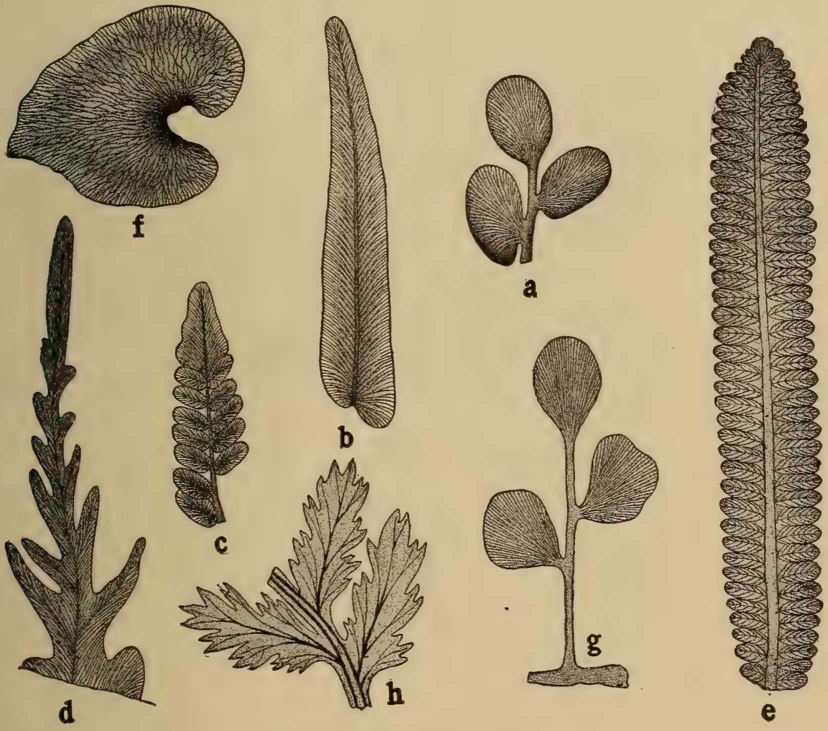

Fig. 276.—A group of fern fronds: *a*, *Neuropteris auriculata*, Brgt.; *b*, *N. angustifolia*, Brgt.; *c*, *N. vermicularis*, Lx.; *d*, *Odontopteris cornuta*, Lx.; *e*, *Pecopteris unita*, Brgt.; *f*, *Dictyopteris rubelia*, Lx.; *g*, *Archæopteris bochsiana*, Goepp.; *h*, *Sphenopteris splendens*, Lx.

boniferous times they had more comprehensive characters, and were in part more primitive than now, and in part more advanced, or at least more closely allied to the higher type, gymnosperms. The fruiting organs, however, were only rarely well preserved, and this limits a precise knowledge of rank and kinship in many species. The majority were herbaceous, but there were many tree fern: some of which reached heights of sixty feet. One of these is represented in the right rear center of the group in Fig. 275. The fronds of several prominent genera are illustrated in Fig. 276, some of which, however, probably belonged to transitional types, and not true ferns. The ferns seem to have been

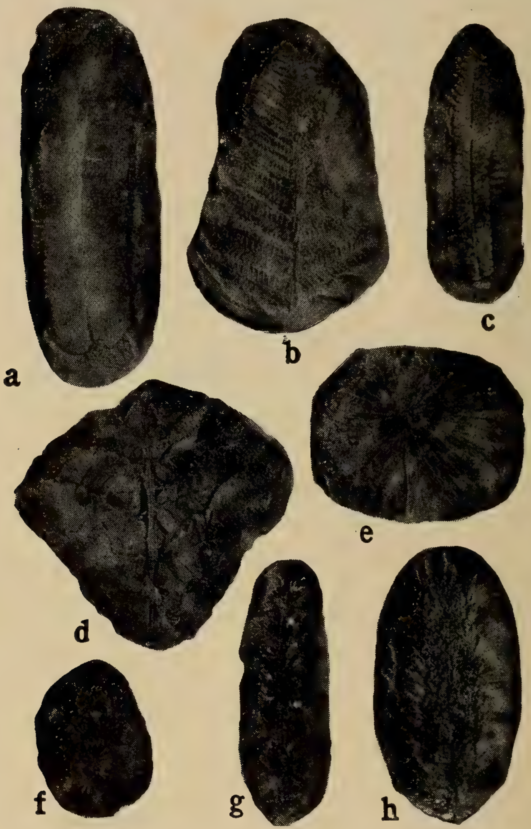

Fig. 277.—A group of plant fossils, occurring in concretions in the Coal Measures at Mazon Creek, Ill.: *a*, *Neuropteris decipiens* Lx.; *b*, and *c*, *Pecopteris unita* Brgt.; *d*, *Callipteridium sp.*; *e*, *Annularia longifolia* Brgt.; *f*, *Annularia spenophylloides* Zenk., *g*, *Cordianthus sp.*, and *h*, *Lepidostrobus sp.*

even then about as well differentiated from the horsetails and lycopods as they are now, and so their ancestry is not revealed by close approach to more primitive forms; but, on the other hand, their relations to their descendants seem to be shown by transitional forms, particularly by an interesting group not yet well defined, the *Cycadofilices*, through which they seem to have evolved into cycads, and perhaps into the whole gymnospermous group, though this is an open question.

The Cycadofilices (Pteridospermæ).[1]—It has recently been ascertained that not a few of the fern-like forms possessed structural features which combine the characteristics of ferns and of cycads, and seem to represent the line of evolution from ferns to cycads. They have hence been called *Cycadofilices* by Potonie.[2] It has been further found that some of these bore seeds, and such have been called *Pteridospermæ* by Oliver and Scott.[3] Of these, the best-known form is *Lyginodendron*, illustrated by the excellent restoration of Scott and Allen (Fig. 278), which exhibits the spiny stems and leaves, the highly dissected foliage, the adventitious roots, and the general aspect. The leaves had well-marked palisades (vertically elongated cells arranged side by side as a protection against too intense sunlight, and hence significant of atmospheric conditions), with the breathing pores (*stomata*) on the underside of the leaf. "The whole structure is altogether comparable to that of a fairly coriaceous fern-leaflet at the present day, and indicates that the conditions to which the structure was adapted could not have been fundamentally different from those which prevail in our own epoch."[4] The limits of the group are not yet known, but it is thought to include *Lyginodendron*, *Heterangium*, *Megaloxylon*, *Cladoxylon*, *Calamopitys*, *Medullosa*, and other genera founded on stem-structure, and some at least of the species referred to *Sphenopteris*, *Alethopteris*, *Neuropteris*, *Odontopteris*, *Callipteris*, *Linopteris*, *Aneimites* (*Adiantes*), *Callipteridium*, and *Lesleya*, genera founded on fronds.

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[1] Scott, Studies in Fossil Botany, Lectures X and XI, and Pres. Add. Roy. Misc. Soc., Apr. 1895, Pt. 2, pp. 137–140. Also David White, Fossil Plants of the Group Cycadofilices, Smithson. Misc. Coll., Vol. 47, Pt. 3, pp. 377, 390, 1905.

[2] Potonie, Lehrbuch die Pflanzenpaleontologie, p. 60, 1899.

[3] Proc. Roy. Soc., Vol. LXXI, 1903, p. 477, and Vol. LXXIII, 1904, p. 4; Phil. Trans., Vol. 697, B, 1904, p. 193. As the bearing of seed places these forms among the gymnosperms in the most extended sense of that term, it is doubtful whether the term *Pteridospermæ* can properly be retained, and the earlier term *Cycadofilices* is given precedence here.

[4] Scott, Studies in Fossil Botany, p. 326.

The frond-genera belong in large part to the stem-genera, the fronds of the *Lyginodendron* being sphenopterids, those of *Medullosa*, neuropterids and alethopterids, and so forth; but the full association of fronds and stems has not yet been determined. How nearly the group grades into the true ferns is not known, but in a general way it constitutes a transition series between the ferns and cycads, and is apparently an illustration of a radical evolution in progress. Initial forms have been identified from the Devonian and Subcarboniferous, and a few are found in the Permian; but the group is essentially Carboniferous, which suggests that probably the evolution was mainly accomplished between the Devonian and the close of the Carboniferous.

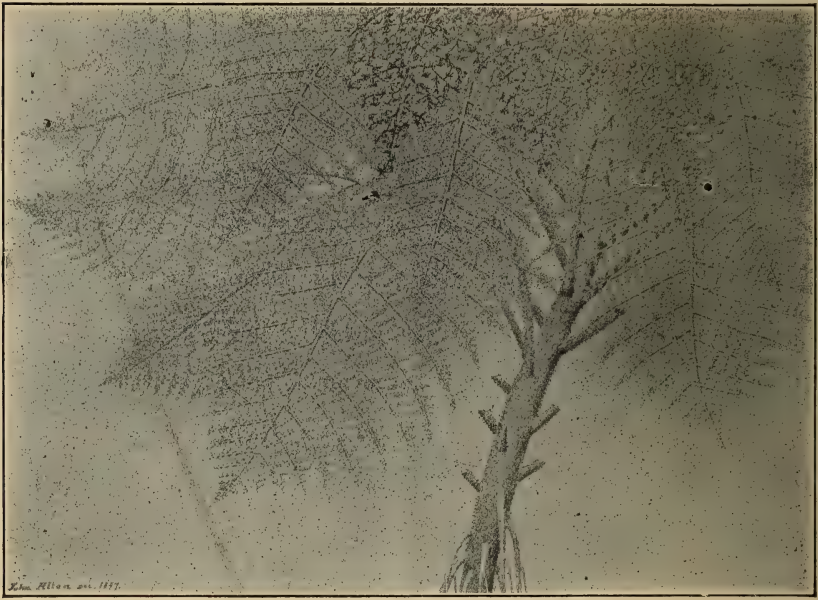
John Allen del. 1897.

Fig. 278.—A typical Cycadofilices, *Lyginodendron oldhamia*. (Restoration by D. H. Scott and J. Allen.)

The Equisetales (calamites, horsetails).—What is now the lowly tribe of horsetails with a single genus, *Equisetum*, constituted a marked feature in the Carboniferous flora, in the form of *Calamites*. These calamarians not only attained much greater sizes, but much higher and more varied organizations than the present equiseta. Even the largest tropical members of to-day, on the eastern slope of the

Andes, have but slender stems 30 or 40 feet long, whereas the Carboniferous calamites reached a foot or two in diameter and probably 60 to 90 feet in height. The calamarians had hollow stems, or a core of pith only, and casts of the interior are among the most common forms of the fossil (Fig. 279, *a*). The constriction at the node in the cast is due to the internal thickening of the walls, the complement of a ring-like expansion externally. The greatest divergence of the stem from the modern forms consisted in a secondary growth, apparently a means of strengthening the stem to meet the exigencies of great growth. The arrangement of the stem tissues was also much more complex than in modern forms. More notable geologically than either of these features was a great development of cork on the outside, sometimes reaching a thickness of two inches or more. This probably implies adaptation to some climatic or other physical condition. Calamite stems have been found showing wounds which had been healed over by wound cork, as in modern times. The branches from the main trunk were comparatively few, and placed in whorls. The leaves also were placed in whorls (Fig. 279, *b*) and were apparently very much bedwarfed from some ancestral form, but not so much so as in the modern type in which the leaves have almost disappeared. In the Devonian *Archeocalamites*, the leaves were forked; in the Carboniferous calamites, they were lanceolate, implying a progressive simplification of the leaf. The upper and lower sides of the leaves were strongly contrasted, the stomata deeply set, and the palisades radially arranged; in short, the structure was of the type adapted to dry weather (xerophytic) as in the pine and in many desert plants, and also, strangely

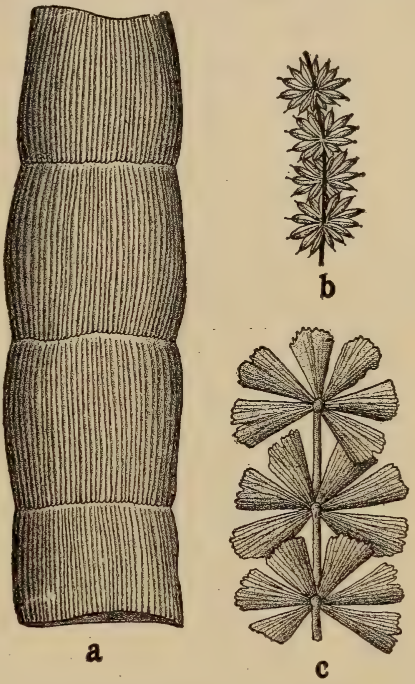

FIG. 279.—Carboniferous Equisetales and Sphenophyllales: *a*, *Calamites cistii*; *b*, *Annularia sphenophylloides*; *c*, *Sphenophyllum longifolium*.

enough, in undrained swamp plants. The trunks arose from stout underground rhizomes. The root structure was of the type commonly found under water or in wet mud. The reproductive organs were in spikes or strobiles, and gave evidence of higher development than now. The calamites were probably associated in thickets or jungles of the cane-brake or bamboo type. Grand'Eury reports great forests of them *in situ* in central France. They probably frequented swamps and lowlands. As the calamites were well differentiated in the Devonian their history may run far back. Their derivation is uncertain, but the next group throws much light on their relations.

The Sphenophyllales.—Recent studies have shown that the graceful, slender plants with whorled leaves, referred to the genus *Sphenophyllum* (Fig. 279, *c*), and formerly classed as calamites, differ in important features from all calamarians, and from the other great divisions of the pteridophytes, and form a class by themselves. Their importance lies chiefly in the fact that while they have certain calamarian features, they have others possessed by the lycopods, which is interpreted to mean that these two groups were united with the *Sphenophyllales* in a common ancestral form.[1] The stems were long, slender, and apparently weak, and so a climbing habit has been inferred. The leaves were without palisades, suggestive of a shady habitat, perhaps one of undergrowth. The class was represented in the Devonian, had its climax in the middle Coal Measures, and continued into the Permian and possibly later.

The Lycopodiales.—This was the master group of the Coal flora, constituting trees of large size and attaining to the highest organization reached by the pteridophytes. From that high estate, they have since fallen to prostrate or weakly ascending plants of moss-like aspect (club mosses, ground pines). The chief genera were *Lepidodendron* and *Sigillaria,* of which the former was the earlier and simpler type. Both take their names from the leaf-scars or leaf-cushions (lepidos = scale, sigilla = seal) which the trunks retained with much persistency, implying little or no exfoliation, though the trunks were affected by secondary growth. The scars are for the most part the leaf-bases or leaf-cushions, rather than the actual scar, which occupies but a small part of the cushion. In the lepidodendrons they are arranged spirally (Fig. 280); in the sigillarians, vertically (Fig. 281).

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[1] Seward, Fossil Plants, p. 413. Scott, Studies in Fossil Botany, p. 494.

The trunks of lepidodendrons were erect and branched dichotomously at a great height, some having been found 100 feet in length, which is probably not the maximum. The leaves were linear or needle-shaped, ranging up to six or seven inches in length, and were set densely on the branches. The breathing pores were confined to the walls of two very deep furrows on the underside of the leaves. Besides a protecting epidermis, there were thick-walled cells within, as in the modern pine, and the mesophyll was loose without palisades, facts of interest as bearing on climatic or other conditions to be discussed later. The manner of reproduction is a point of peculiar interest, for in some cases the fruit seems to have taken on the characteristics of seeds rather than spores, making the development of the lycopods fall into analogy with that of the fern group, in passing from the spore-bearing to the seed-bearing habit. It is not yet known whether any of these seed-bearing lycopods developed into permanent gymnospermous types or not. One form of the fruit was distinctly winged, and other forms showed adaptation to transportation by wind. Over 100 species have been described.

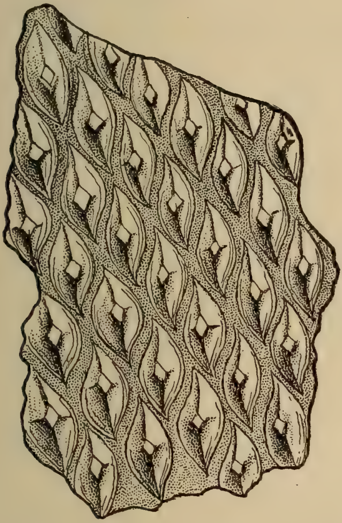

FIG. 280.—Leaf markings of a lepidodendron, *Lycopodites welthermianum*, St.

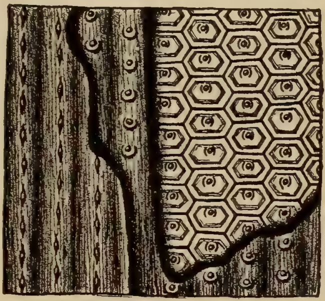

FIG. 281.—Leaf markings of a sigillarian.

The sigillarians differed from the lepidodendrons in being almost entirely unbranched. They were perhaps the largest of the Carboniferous trees, their ribbed trunks being known to reach six feet in diameter, and 100 feet or more in height. As in lepidodendrons, the stems were densely clothed with erect, rigid, linear leaves, which had two deep furrows on the under side to which the breathing pores were confined. The pores were protected still further by hairs in the furrows. The sigillarians, like the lepidodendrons, have secondary wood and a thick cork layer. The degree of development of cork is almost unequalled in modern trees, except in the cork-oak and its allies.

Stigmaria were the roots, or perhaps stolons, of sigillarians and probably of lepidodendrons, the scars that mark them being the points of attachment of appendages or rootlets. Tap roots are never present, the main roots, usually four in number at the start, spreading horizontally.

We have entered thus into detail respecting these remarkable plants, partly because of the interest which they have as the constituents of the first-known great forests, and partly because not a few of their features are suggestive of the climatic and other physical conditions by which they were surrounded, a question to be considered presently.

The lepidodendrons seem to have reached their climax early in the Coal Measure period and to have declined during the later portion, so that they had nearly all disappeared by the close of the period. In the latter part of the period, the sigillarians passed the lepidodendrons in abundance, but they also were decidedly on the wane at its close. Whether or not this rather sudden decline, followed by an early extinction, was connected with such climatic changes as are indicated by the glaciation of India, Australia, and South Africa, and which seem to have occurred not far from this time, is a question which naturally arises, but it cannot be answered demonstratively at present.

The Cordaites.—This was a remarkable extinct family of the gymnospermous type, having alliances with the cycads, conifers, and ginkgos, and yet many distinctive features of its own. The cordaites were tall, rather slender trees, reaching two or more feet in diameter, and 90 feet or more in height. The wood was of the coniferous type, covered, as in so many other plants of the period, by a thick complex bark. The trunks had a large pith. The leaves were parallel veined, suggestive of monocotyls of the yucca type, and sometimes attained a length of six feet and a width of half a foot. They were preserved in great abundance and make up a large part of some beds of coal. The leaf-structure combined characters now possessed by certain conifers, with others possessed by certain cycads. Palisades were sometimes well developed, though sometimes replaced by water-storage tissues. In one form observed, the leaf had a distinctly fleshy character, as if adapted to xerophytic life.[1] The floral organs were peculiar to the family and have been worked out with marvelous success, even the structure of the pollen having been determined. The inflorescence took the form of separate male and female catkins, arranged on slender stalks attached to the stem between the leaves. The seeds (*Cardiocarpus*) were of the cycadian rather than of the conifer type, and were very abundant and sometimes winged, with a view to wind transportation. In the working out of the structure of the cordaites, it has been shown that many fossils referred, on account of the wood structure, to conifers (e.g. *Dadoxylon*, *Araucarioxylon*), are cordaitean, and that the forms known as *Artisia* or *Sternbergia* are casts of the pith-cavity of cordaites; and not a few other misinterpretations have been corrected.

The transfer of so many supposed conifers to the cordaites leaves it doubtful whether any true conifers are recorded from the Carboniferous, though they were probably represented in the Permian. Numerous seeds are found in Carboniferous beds that cannot certainly be referred to cordaites or other known forms, some of which may belong to conifers. As previously remarked, the upland vegetation is not known, and it is not impossible that conifers, a type specially suited to an upland habitat, prevailed there.

Cycads have been commonly reported from the Carboniferous, but the evidence remains inconclusive; the same may be said of the ginkgos. There is no evidence whatever of angiosperms.

The Distribution of the Carboniferous Flora.

The Coal flora of North America and that of Europe were strikingly similar, implying close geographic relations and like conditions. Nearly all the genera, and about one third of the species, were identical. In part at least, this flora extended to high latitudes in the environs of the North Atlantic, as shown by Heer,[1] and others. Species of *Astrophyllites*, *Sphenopteris*, *Sphenophyllum*, *Lepidodendron*, *Stigmaria*, and *Cordaites* have been found in Spitzbergen, including the cosmopolitan species *Lepidodendron sternbergii* and *Cordaites borassifolius*. *Sphenopteris* is reported from Melville Island in association with coal. A very similar flora is found in the Coal Deposits of China, embracing *Callipteridium*, *Neuropteris*, *Palæopteris*, *Sphenopteris*, *Calamites*, *Sphenophyllum*, *Lepidodendron*, and *Cordaites*. In southern Asia neither the record nor its bearing is altogether clear. In the Salt Range in northwestern India, the marine "Productus beds" contain some species regarded as Carboniferous, commingled with others of more recent aspect, while at its base are bowlder beds with glacial markings, implying conditions quite at variance with the warmth and uniformity usually postulated for the Coal Measures period. In the center of the peninsula of India, the Talchir formation contains both coal and glacial beds, and is referred by authors with hesitation to the Upper Carboniferous and Permian. In Australia, the earliest coal-beds contain *Lepidodendron* and *Cordaites*, but the chief coal-beds contain *Glossopteris* (a tongue-shaped fern) and its associates, to be described later. Closely associated with these coal-beds are glacial beds also to be described later. The *Glossopteris* flora characterizes all the plant-beds that are later than the glacial beds. Species of *Glossopteris* seem to have appeared before the formation of the glacial beds, and perhaps as early as the Lower Carboniferous. In South Africa there are beds containing *Lepidodendron* and other Carboniferous species, overlain unconformably by the Dwyka Conglomerate, a part of which is glacial, and above which the *Glossopteris* flora prevails.

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[1] Scott, Studies in Fossil Botany, p. 425.

Taking the phenomena of India, Australia, and South Africa together, they make a puzzling combination. If the chief coal-beds be referred to the Carboniferous proper, it introduces glacial beds, and a great floral break, into the midst of a system which has usually been held to be marked by great uniformity the world over. It is, however, more probable that the glacial beds and all the formations above them are to be referred to the Permian period, and this interpretation will be followed in this work. Even when these extraordinary formations are eliminated, it is not wholly clear that the flora of the southern regions was very closely identical with that of the northern.

[1] Flora Fossilis Arctica, IV, 1877.

Lepidodendron and *Sigillaria* extended to that region, but *Glossopteris*, singularly related to the glacial formations, seems to have been contemporaneous with them, while it did not reach Europe till the late Permian and is not known to have reached North America at all. With the present imperfect data for the southern hemisphere, it is uncertain whether the northern coal flora, as a whole, ever extended to that region, although some of its leading genera certainly did. While recognizing the great uniformity of the Carboniferous vegetation of North America, Europe, and a portion of Asia, it is prudent to hold opinion in reserve relative to the southern hemisphere.

Climatic Implications of the Coal-plants.

While the foregoing facts are fresh in mind, it may be best to inquire what suggestions arise from the characters of the plants relative to the atmospheric conditions under which the Coal flora grew. Two rather antagonistic views relative to these conditions have been held. The older of these views regards the accumulation of the thick deposits of coal as evidence of a very luxuriant growth of vegetation, which in turn has been thought to imply a very warm, moist atmosphere, heavily charged with carbon dioxide. The abundance of tree-ferns and of large equiseta, such as now are found only in tropical countries, has been thought to strongly support this view. The occurrence of coal deposits and of the Coal flora in high latitudes has been appealed to as proof of uniformity of climate. This view was formerly held almost unanimously, and still preponderates. Its grounds seem to be strong. The alternative view which has grown up in recent years postulates less rapidity of growth, less warmth and moisture, and more diversity of atmospheric states, as well as a nearer approach to the present atmospheric constitution, though it accepts a somewhat increased percentage of carbon dioxide, and assumes a milder and more uniform climate than the present. The basis of this view (held in different degrees and phases by different geologists) is found in the following considerations. Great thicknesses of coal do not necessarily imply rapid accumulation, any more than great thicknesses of limestone. Given favorable conditions of preservation, a slow growth will produce the thicknesses realized. At present the accumulation of peat, the nearest analogue of coal formation, indeed the first step in coal formation, is most favored in cool climates, and is chiefly taking place in high latitudes, though it is also taking place in favored situations in low latitudes. These situations, however, are rather rare and local, while peat formation in high latitudes covers great areas. A high temperature, while it promotes a luxuriant growth of vegetation, also promotes, in an even higher degree, decomposition, under usual conditions.

The characteristic foliage of a warm, moist atmosphere takes the form of broad leaves with a thin epidermis and with many and large breathing pores, affording abundant facilities for the transpiration of moisture. The dominant plants of the Coal flora, notably the characteristic lepidodendrons and sigillarias, have narrow leaves with the breathing pores confined to deep furrows on the under side, and even then, in some cases, protected by hairs, devices that are common when the plant must guard itself against too rapid expiration of moisture, devices technically known as *xerophytic.* These have been carefully noted in the preceding descriptions, because of their possible significance. It was also observed that most of the leaves of the forest-trees were protected from too great action of the sunlight, by palisade cells on the upper sides of the leaves. It was noted further that most of the trees were clothed by unusually thick corky bark, as though protection from external conditions was needed. It has been suggested, indeed, that this bark was succulent, rather than corky, but it is the part best preserved, and, according to Dawson, often makes up a large part of the coal, because the wood and the foliage more largely perished, facts hardly consistent with a succulent nature. The remarkable preservation of the leaf scars is interpreted, on the one side, to mean an extremely rapid growth and quick burial, and on the other side, to mean a texture very resistant to decomposition, and an atmosphere unfavorable to decomposition, by reason of dryness or coolness. Taken as a whole, the thickness of the bark, its superior resistance to decomposition, the form of the leaves, presenting small surfaces rather than expansive ones, with their strong sclerenchymatous tissues, their palisades, and their restricted and protected stomata, give a pronounced xerophytic aspect to the overgrowth made up of lepidodendrons, sigillarias, calamites, and cordaites. It is not equally so with the undergrowth, the ferns, and the sphenophylls, but this should not be expected of shaded plants, unless the aridity was extreme.

The force of the inference from the xerophytic aspect of the overgrowth is much weakened, however, by the fact that the vegetation of undrained swamps and bogs assumes many of these xerophytic features, which, in such cases, obviously become pseudoxerophytic. A satisfactory explanation of this phenomenon has not yet been found, nor has its extent and its limitations, either in respect to the nature and degree of swampiness necessary to produce it, or in respect to the kinds of plants or the parts of plants affected, been so thoroughly worked out as to permit a close application to the problem in hand. It is obvious that to fit the case, marsh or bog conditions must have produced pseudoxerophytic adaptations in the great mass of the tree growth, but not in the ferns and sphenophyllous plants. The effects must apparently also be extended to all plants brought into the depositing basins by drainage, whether these were true swamp plants or not, unless a closer study of the Coal flora shall show that the xerophytic aspect was not assumed by all species of the trees involved. It is clear that a more critical study of the problem on all sides is necessary before a final conclusion can be reached. This will become the more apparent when we bring into consideration, as we must a little later, the extraordinary phenomena of glaciation in low latitudes, alternating with coal deposition, though the flora then involved was not identical with that here considered. It bears, however, on the question whether thick coal-beds necessarily mean rapid growth. It will be found that the coal-beds that lie *between* the glacial beds, attained the usual thicknesses.

The influence of increased carbon dioxide on plant growth.—It has been commonly believed that a moderate increase of carbon dioxide in the air would promote a more luxuriant plant growth, and some experiments seem to confirm this.[1] In recent experiments by Brown and Escombe,[2] on the contrary, where an increase of carbon dioxide to the extent of three or more times the normal amount was used, the growth of the plants employed (angiosperms) was appreciably decreased, the structure was adversely modified, the growth of the internodes was checked, the leaves became smaller, and there were changes of a pauperitic nature in the tissues and general aspect of the plant, while the flowering was greatly restricted, and in some cases prevented altogether. At the same time it was shown that, temporarily, the photosynthesis of the carbon dioxide was increased, and that the leaves were engorged with starch. The inference was drawn that the dwarfing effects were due to a disturbance in the adjustments of the plant. This might perhaps be overcome in time by means of a gradual change, so that no safe conclusions can be drawn relative to the effects of a variation in the proportion of carbon dioxide brought about by a change of geological slowness. It is to be noted, too, that the plants experimented on were all angiosperms, and may be more subject to disturbance by increased carbon dioxide than the lower groups which lived in Carboniferous times.

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[1] E. C. Tealoresco, Influence de l'Acide Carbonique sur la Forme et la Structure des Plantes. Rev. Gen. de Botanique, Vol. II, 1899.

[2] The Influence of Varying Amounts of Carbon Dioxide in the Air on the Photosynthetic Process of Leaves and on the Mode of Growth of Plants. Proc. Roy. Soc., London, LXX, 1902, p. 379; On the Influence of an Excess of Carbon Dioxide in the Air on the Form and Internal Structure of Plants, ibid., p. 413

The seemingly conflicting import of the preceding considerations lends uncertainty to all inferences, and invites reserve in interpretation, as well as more critical study in the field and laboratory.

II. The Land Animals.

The animal life of the land embraced amphibians, insects, spiders, scorpions, and myriapods. The development of the amphibians was the most significant feature, for it was the initiation of the great line of land vertebrates, the ruling dynasty from that day to this.

The rise of the amphibians.—Tracks attributed to amphibians occur as early as the Devonian. In the Mississippian, there is a similar record of a four-footed animal of thirteen-inch stride, believed to have been made by one of the primitive amphibians, but in neither of these periods have any relics of the animal itself been found in America, and only imperfect fossils in Europe. These are sufficient, however, to fairly attest the presence of land vertebrates. The amphibian relics from the Carboniferous beds confirm their earlier presence by such a degree of structural differentiation as to clearly imply a long antecedent existence. The conditions of the Devonian period must surely have been peculiarly favorable for the evolution of the amphibians, for fish having structures akin to the amphibians, and apparently susceptible of amphibian development abounded, and there was much shifting of land and water areas, and doubtless much competition and conflict and forcing of new adaptations, as a result. The emergencies of shoaling water and shifting drainage must inevitably have called into play such powers of air-breathing as the fishes of the time possessed, as well as such ability as they may have had to use the paired fins in locomotion on the land. The great development of the lung-fishes in the Devonian is perhaps one result of this, and they have been regarded as the possible ancestors of the amphibians. This view is now largely abandoned for anatomical reasons, and some branch or branches of the crossopterygians regarded as the more probable ancestors. The connecting link, however, yet awaits discovery; but evolution from some form of fish as early as the Devonian period, if not earlier, is regarded as extremely probable. Because of the fatal effects of salt water on modern amphibians, and for other reasons discussed in connection with the Devonian fish, there is a presumption that the evolution took place in and from fresh water, not unlikely in the continental interior where fluctuations in drainage and precipitation might well have been greater than on the coast, and hence the scantiness of the transition record. Even in the early Carboniferous the record was poor, and relics of amphibians appear in abundance only in the later Coal Measures. They were then already differentiated into five suborders, *Branchiosauria*, *Aistopoda*, *Microsauria*, *Temnospondyli*, and *Labyrinthodonta*.[1] These were all still rather primitive in structure, but they were quite far from being the real transition forms. They are the most primitive terrestrial vertebrates known at present, and if not really the ancestors of all later land vertebrates, they probably represent their general nature. They all seem to have been low, elongate forms of salamandrine aspect, and are classed as stegocephalians (roofed-head), their heads being well roofed over by the bony plates of the skull. They have also been termed labyrinthodonts, from the intricate infolding of the dentine of the teeth of one of the suborders, but the others do not possess the character.

The *Branchiosauria* were perhaps the most primitive in structure, though they have not been found earlier than some of the more advanced types. They were small and salamander-like in form, with short, stumpy, weak limbs and abbreviated tails. The teeth were simple, hollow cones, not labyrinthine. Forms in all stages of growth

[1] The classification here followed is slightly modified from that of Smith Woodward, Vert. Pal., from whom many of the following facts are drawn.

have been found, showing that gills were possessed in the early stages, that they were lost later, and that finally the adult amphibian form was assumed, thus establishing fully the amphibian metamorphism. The ventral surface was usually protected by small overlapping plates or scutes, and these sometimes extended to the legs and back. Two genera (from Linton, Ohio) have been referred to this suborder, perhaps with some doubt. Other genera are known from the Permian of Bohemia, Saxony, and France.

The *Aistopoda* were snake-like forms whose limbs had been atrophied, which implies that a degenerative development had already taken place. The elongation of their bodies involved a notable multiplication of the vertebræ, one form having no less than 150. The animals, or some of them, were protected by scutes beneath, and were armed with small ossicles on the back. Their teeth were simple hollow cones without infolding. Two genera (*Phlegethontia* and *Molgophis*) have been found in Ohio, one or two in the Carboniferous of Ireland, and two in the Lower Permian of Bohemia. One of the Irish genera (*Dolichosoma*) is very closely related to the Ohio forms, and they have even been supposed to be identical, a significant fact in view of their wide separation and their limited means of dispersion.

The *Microsauria* were like the branchiosaurs in having salamandrine forms, and conical teeth with simple or only slightly infolded walls. Compared with the other suborders, their vertebræ were more like those of the modern reptiles, their skeletons were more completely ossified, their skulls contained less cartilage, and their limbs were longer and stronger. Some of them at least probably ran with lizard-like agility, and perhaps climbed readily, since many have been found in the trunks and stumps of trees, as in the coal-mines of South Joggins, Nova Scotia. A score or more of genera, often imperfectly known, are referred to this suborder from the Carboniferous of America (Nova Scotia and Ohio), and from the Carboniferous (Ireland, Fig. 282) and the Lower Permian (Bohemia and Saxony) of Europe. They were in some respects highly differentiated, and are regarded by some paleontologists as the ancestors of some or all the reptiles.

The true labyrinthodonts were doubtless the largest and most characteristic amphibians of the period, though yet imperfectly known. They take their name from the form of the dentine of their teeth, which was usually intricately infolded, giving to the cross-section a beautiful labyrinthine arrangement, as shown in Fig. 283. It will be recalled that the holoptychian fishes had a very similar dental structure. The labyrinthodonts differ from the forms referred to the next suborder in having well ossified, biconcave vertebræ, a specialization known to have been reached early in this period. Moreover, the teeth are much more highly labyrinthine than in the known *Temnospondyli*. These features remove the labyrinthodonts from the direct line of ancestry of some, if not of all, the reptiles. Their skulls reached a maximum length of half a meter or more in the Carboniferous period, and by Triassic times, they had attained a length of at least a meter and a quarter, from which the full length of the animal is inferred to have been four or five meters; but in general, if compared with modern crocodilians, they must be regarded as of only moderate size.

The *Temnospondyli* differed from the true labyrinthodonts in the divided (rhachitomous) structure of their vertebræ, whence the name. Such vertebræ are thought to have been possessed by the earliest known amphibians from the Lower Carboniferous of Scotland, and forms with similar vertebræ have been found in the upper Carboniferous. The *Temnospondyli* are, however, imperfectly known in the Carboniferous, though they doubtless lived then in abundance and may have made many of the known footprints. They reached their highest development in the Permian, and are supposed by many paleontologists to be the ancestors of all modern reptiles.

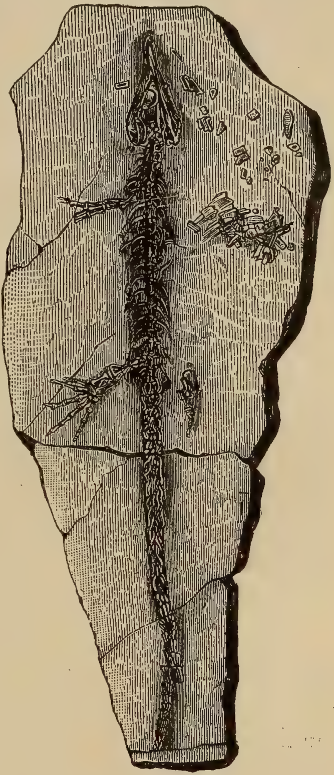

Fig. 282.—Carboniferous amphibian *Lepterpeton dobbsi* Huxley: a microsaurian from Kilkenny, Ireland, about $\frac{2}{5}$ natural size. (Zittel.)

Not much is known of the food and life-habits of any of these amphibians. From their teeth, it is inferred that they were predaceous and lived on fish, crustaceans, insects, and other amphibians. At

South Joggins, Dawson took thirteen skeletons representing different amphibian species from a single sigillarian stump. As such stumps sometimes contained land shells and myriapods, together with amphibian skeletons, it has been inferred that such amphibians were climbers, and lived on mollusks, myriapods, and similar land life.

In certain places amphibian tracks occur in great abundance, implying that the animals frequented muddy flats; in some places also their remains are common; it is therefore inferred that they were abundant, at least locally. From their wide differences of structure and their considerable specialization, it is inferred that they enjoyed conditions favorable both to divergence of type and to development of individual structure, and these should have been found in the new field upon which, almost or quite without rivals, they had entered,—the empire of the land.

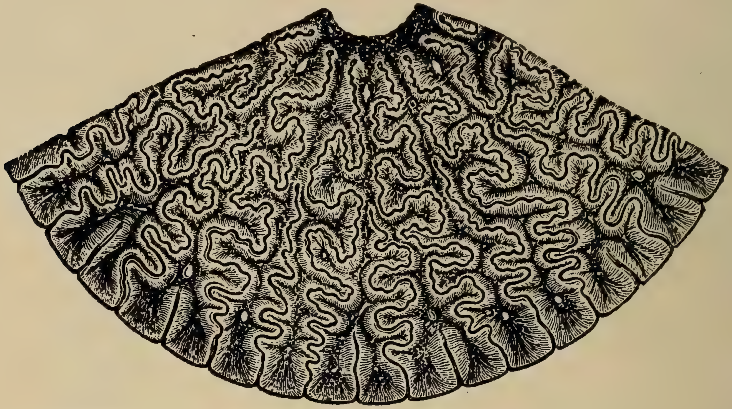

Fig. 283.—Cross-section of the tooth of a Labyrinthodont, of later date (Triassic). *Mastodonsaurus giganteus*, highly magnified, showing the deep intricate infoldings of the walls of the tooth. (From Woodward after Owen.)

As the evolution of the amphibians constituted the ascent of the vertebrate type from the water and the beginning of their dominance of the land, the event may be well regarded as one of the most significant in the earlier history of the earth.

The marked development of insects.[1]—The identification of 400 species of Carboniferous insects from American deposits and a comparable number from the European, previous to 1891, with constant additions since, indicates the great development of this class. They were still, for the most part, of the rather primitive synthetic types, often uniting characters not now found in the same order, and sometimes embracing strange combinations, as a neuropterous wing on an orthopterous body; but advancing differentiation was already manifested. The orthopterous group, embracing cockroaches (Fig. 284, *i*), locusts, crickets, and walking-sticks, were greatly in the lead, followed

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[1] Scudder, Bull. No. 71, U. S. Geol. Surv., 1891, and works there referred to. Brongniart, Researches pour servir a l'histoire des Insectes Fossiles des Temps Primaires, 1894. Dawson, J. W., Synopsis of the air-breathing animals of the Paleozoic in Canada up to 1894.

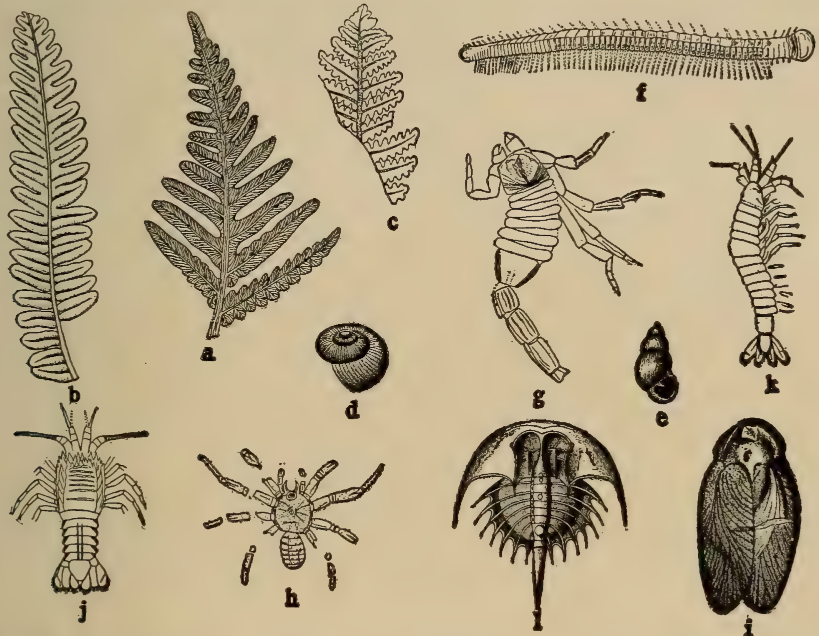

FIG. 284.—CARBONIFEROUS TERRESTRIAL AND FRESH-WATER LIFE. *Plants: a, Callipteridium mansfieldi* Lesq., *b* and *c*, *Callipteridium membranaceum* Lesq., two species of ferns. *Land shells: d, Zonites priscus* Carp., *e*, *Pupa vermilionensis* Bradley. These land snails have been referred to genera living at the present time, and although this reference may eventually prove to be incorrect, they are at least close relatives of recent genera. *Insects, etc.: f, Euphoberia armigera* M. and W., a Carboniferous myriapod or thousand-legged worm; *g*, *Eoscorpius carbonarius*, M and W., a scorpion very similar in type to living forms; *h*, *Arthrolycosa antiqua* Harger, a spider more primitive than recent forms as seen by the segmentation of the abdomen; *i*, *Progonoblattina columbiana* Scudd , one of the allies of the modern cockroaches which were the most conspicuous members of the Carboniferous insect fauna. *Crustacea: j*, *Anthrapalæmon gracilis* M. and W., *k*, *Palæocaris typus* M. and W., two types of crustaceans found in the Mazon Creek nodules; *l*, *Prestwichia danæ* M. and W., one of the early allies of the modern horse-shoe crab. (Weller.)

by the neuropterous group, represented by ancestral mayflies, these two groups making up perhaps 90 per cent of the whole. *Hemiptera* (bugs), which had appeared earlier, and possibly *Coleoptera* (beetles) were present, but there is no evidence of bees or other *Hymenoptera*, or of butterflies, moths or other *Lepidoptera*, and no probability of their existence, since the flowering vegetation on which they are dependent had not yet appeared. There is also no record of flies (*Diptera*). The evolution of the class was therefore quite one-sided, and essentially ortho-neuropterous. Curious forms were developed within these orders, and rather remarkable dimensions appeared in some cases, spreads of wing of a foot or more being reported. The fossilization was very irregular, but rather wide-spread, but the species *seem* to be very local. This may be due to the probable fact that the different localities where they have been found represent different horizons. If this alternative be accepted, it probably implies a rather rapid change of species, which is not improbable under the extraordinary conditions that surrounded them.

Spiders, scorpions, and myriopods.—As early as 1890 Scudder had reported 75 species of arachnids (Fig. 284, *h*) and 40 species of myriopods (Fig. 284, *f*); scorpions (Fig. 284, *g*) also were present. Some of the myriopods were vegetable eaters, but one can only wonder what all these spiders and scorpions lived on. The record probably does not tell the whole story.

Land snails (Fig. 284, *d* and *e*), in several species, have been identified.

From the foregoing it is apparent that the air-breathing community had become somewhat large and diverse, embracing a varied group of amphibians, many insects, spiders, and myriopods, and some scorpions and snails. It is obvious that all speculative assignments of carbon dioxide in the atmosphere must be limited to quantities compatible with this life, and the life of flying insects is of a high order of activity.

III. THE FRESH-WATER LIFE.

Besides fresh-water plants, the life of the land waters appears to have consisted of certain amphibians (and of all in their early stages), of fishes, mollusks, crustaceans, probably of the larval forms of certain amphibious insects, and doubtless of many unknown forms. Aside from the developments of the fresh-water fish and of the amphibians, which have already been sufficiently emphasized, perhaps the most suggestive feature was the association of the arthropods with other forms of life. Eurypterids were still in existence, and their relics are so intimately associated with beautifully preserved ferns, calamites, insects, spiders and scorpions as to leave no reasonable doubt that they were true fresh-water forms. In the more notable localities, as at Mazon Creek, Illinois, and Cannelton, Pennsylvania, the fern fronds were preserved with almost perfect fidelity, and without the coiling, crumpling and shredding that would inevitably have attended transportation for any notable distance. At the famous locality on Mazon Creek, uncrumpled fronds form the centers of thousands of concretions (Fig. 277), and insects, spiders, scorpions and eurypterids form the centers of others associated with them. All must have been fossilized with a minimum of transportation, and under the most quiet conditions. Almost equally instructive is the association at Cannelton, shown in Fig. 285, though the vegetation is more fragmentary. A not-distant relative of the eurypterids was present in the beautiful *Prestwichia danæ* (Fig. 284, *l*), whose resemblance to the trilobites on the one hand, and to the king crabs on the other is rather striking, and probably implies a remote ancestral relationship. There were also malacostracans, resembling cray-fish, but referred to a separate order (Fig. 284, *j*), and other crustaceans of shrimp-like appearance (Fig. 284, *k*). Taken together these show a very interesting deployment of the arthropods, and if this be considered in connection with the peculiar association of the eurypterids, ostracoderms, and fishes, of the Devonian and late Silurian, it is not without suggestiveness in connection with the views of Patten (p. 482) relative to the genetic relations of the arthropods and vertebrates, and of Cham-

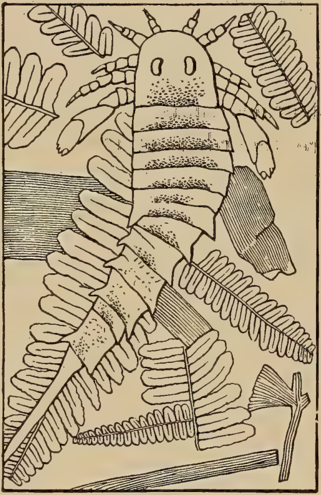

FIG. 285.—Natural association of *Eurypterus mansfieldi* with ferns and calamites. (From Dana after Hall.)

berlin relative to the origin of the latter in fresh waters.[1] It will perhaps yet appear that fresh water was the environment under which some of the most radical of all the biological evolutions took place.

Another phase of association of the fresh-water life of the Carboniferous times is well preserved in a cannel coal deposit at Linton, Ohio.[2] This coal is thought to have been formed from fine vegetable débris borne into a fresh-water lake or lagoon, where it settled and buried the relics of the local life, which consisted of more than 20 species of fishes, and nearly 40 species of aquatic amphibians. Newbury thought that their individual numbers mounted into the millions. Among the fishes were crossopterygians (*Cœlacanthus* and *Rhizodus*), actinopterygians (*Eurylepis*), dipnoans (*Ctenodus*) and the peculiar pleuracanthids (*Orthacanthus, Diplodus, Compsacanthus*). These last are regarded as elasmobranchs which then, as now, lived in fresh water, though mainly marine. The amphibians belonged to the suborders previously described.

IV. The Marine Life.

Because of the remarkably close adjustment of the sea-level to broad areas of marshes and flat lands, two phases of sea life had sufficient prevalence to be worthy of note. The first consisted of those forms that habitually occupied the thin edges of the sea which, in the form of estuaries, lagoons and shoals, crept in and out on the border tract as the relations of land and sea oscillated, while the second embraced the life of the more open seas. This distinction had doubtless always existed, but had not before reached equal importance, and the first phase was not usually well preserved, whereas, in the coal regions of this period, it constitutes the better part of the record. In this phase, where sandy and muddy flats prevailed, the pelecypods and gastropods, with certain of the fishes, predominated, while in the more open seas the brachiopods, cephalopods and the clear-water types more largely predominated.

The progress of the fishes.—It is difficult to tell which of the fishes should be regarded as marine, which as fresh water, and which as common to salt and fresh water. It seems clear that much the larger number of those found in the American Coal Measures lived in fresh water; whether also in salt water is uncertain. It is extremely probable that the sharks armed with shell-crushing teeth (the cochliodonts and psammodonts) were chiefly marine, and that they continued to be abundant through this period, though probably less dominant than in the extensive shell-bearing seas of the Mississippian, while the sharks armed with cutting teeth were also largely marine, but less dominantly so. There was further progress in adaptation to swift movement and in acquiring shapeliness of outline.

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[1] Jour. of Geol., Vol. VIII, p. 400.

[2] Newberry, Mon. XVI, U. S. Geol. Surv., 1889, p. 211.

Changes in the aspects of the mollusks.—By reference to the pelecypods represented in Fig. 286, *a, b, c, d, e,* and *f,* and by comparison with previous figures, it will be noted that this group had assumed an appreciably more modern aspect. They are scarcely Paleozoic in the sense of being very ancient. The period was doubtless very favorable to their advance, by presenting an expansive but shifting and oscillating habitat, that both invited and forced mutational plasticity. The gastropods, on the other hand (Fig. 286, *g, h, i, j, k*), show less advance over the earlier types. They resemble those of the Genevieve and even of the Devonian fauna, though quite unlike those of the Osage. On the whole, they still present a distinctly Paleozoic aspect.

Association of lingering and advanced cephalopods.—There was a notable juxtaposition of very ancient and of relatively modern cephalopod types, the former represented by very straight, plain, small orthoceratites (Fig. 286, *r*) that might well belong to the earliest Paleozoic epoch, the latter by closely coiled goniatites (Fig. 286, *q*) with curved sutures that might well be an initial Mesozoic type. The orthoceratites were about to take their departure, the goniatites were about to evolve into the ammonites, the reigning type of the Mesozoic era.

The brachiopods.—As usual the brachiopods held an important place, and their general facies was like that of the Upper Mississippian. *Productus* was the leading form and had many species (Fig. 286, *t, u,* and *v*), while *Athyris, Chonetes* (Fig. 286, *z*), *Spiriferina* (Fig. 286, *y*), and other genera common in the Mississippian persisted in abundance, but in new species. Spirifers also were again common, some of them exhibiting an advanced state of bifurcation of the plications, as in *Spirifer cameratus* (Fig. 286, *dd*). Some species of the brachiopods were long-lived, and some ranged not only through northern America

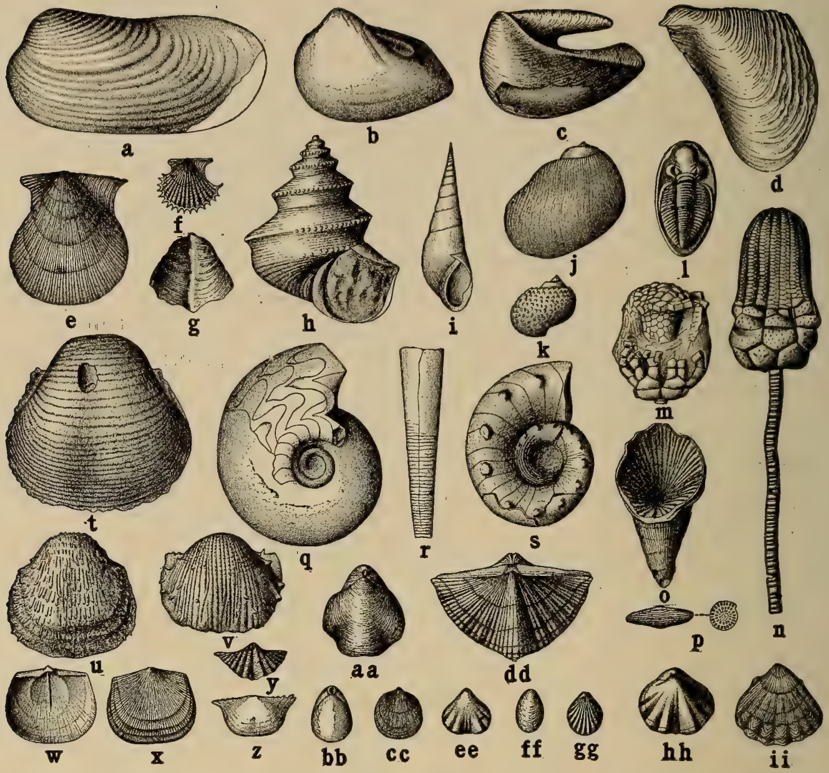

Fig. 286.—The Pennsylvanian (Coal Measures) Fauna. *Pelecypoda: a, Allorisma subcuneata* M. and H., *b, Schizodus wheeleri* Swall., *c, Monopteria longispina* Cox, *d, Myalina recurvirostris*, M. and W., *e, Aviculopecten occidentalis* Shum., *f, Aviculopecten carboniferus* Stev.; a group of six pelecypods of types more or less common in the Pennsylvanian; their relationships for the most part are with forms in the Mississippian faunas. *Gastropoda: g, Bellerophon percarinatus* Con., *h, Worthenia tabulata* (Con.), *i, Meekospira peracuta* (M. and W.), *j, Naticopsis altonensis* McCh., *k, Trachydomia wheeleri* (Swall.); a group of gastropods showing a variety of forms. These Carboniferous members of the class agree with their ancestors in the entire apertures, the canaliculate aperture so common in recent marine gastropods being introduced later. *Trilobita: l, Phillipsia major* Shum., almost the last of the trilobites; this genus persists into the Permian, and then becomes extinct. *Crinoidea: m, Hydreionocrinus acanthoporus* M. and W., showing the extravagant development of the ventral sack; *n, Eupachycrinus magister* M. and G., with biserial arms, a type of arm structure introduced late in the history of the *Inadunata*, but very early in the *Camerata*. This form approaches some of its Mesozoic relatives, especially such Triassic forms as *Encrinus*. *Coral: o, Zaphrentis gibsonii* White. Corals are rare in this fauna, and are nearly all of the horn-shaped genera. *Protozoa: p, Fusulina secalicus* Say, a little foraminifer that sometimes constitutes nearly the entire calcareous material of important limestone beds. It occurs abundantly in America, Asia, and Europe. *Cephalopoda: q, Paralegoceras newsomi* Smith, *r, Orthoceras cribrosum* Gein., *s. Temnocheilus forbesianus* (McCh.); three figures representing three types of cephalopods in the Carboniferous, viz.: (1) the goniatites, with their lobed sutures which gave rise to the Mesozoic ammonites; (2) the straight orthoceratites which

and Eurasia, but into the far Orient and Australasia. Among these wide-ranging species were *Hustedia mormoni* (Fig. 286, *gg*), *Rhipidomella pecosi, Enteletes hemiplicata* (Fig. 286 *hh*), *Productus semireticulatus, P. cora, P. costatus* (Fig. 286, *v*). Some of these, as *P. semireticulatus* and *P. cora,* extended up into the Permian. Other representative brachiopods are illustrated in Fig. 286, *w, x, aa, bb, cc, ee, ff,* and *ii*.

A new phase of the crinoids.—The crinoids were a smaller factor in the fauna than might have been expected from their previous and subsequent history. The cystoids and blastoids seem to have disappeared previously, and no starfishes have been recognized, though they were doubtless present; sea-urchins were rare. The camerate crinoids do not appear, and the inadunate crinoids took the leading place, and celebrated their accession to crinoidal supremacy by developing the ventral sac to unseemly dimensions until it sometimes protruded beyond the arms with balloon-like, or mushroom-like, inflation (Fig. 286, *m*). It is needless to say that these ventral excesses did not last long, and the moral is obvious. Other genera developed in the opposite direction, and lived on becomingly, giving rise, as it would appear, to some of the Mesozoic types. The form *Eupachycrinus magister* (Fig. 286, *n*) is notable as bearing a Mesozoic aspect.

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were nearing the time of their extinction, and (3) the conservative, simple sutured nautiloids which persisted from the Ordovician to the present. In the Carboniferous, the nautiloids were especially characterized by their nodose ornamentation. *Brachiopods: t, Productus symmetricus* McCh., *u, Productus nebrascensis* Owen, *v, Productus costatus* Sow ; the genus *Productus* is one of the most common in the Carboniferous faunas, and these are three of the common species; *w–x, Derbyia crassa* (M and H.), representative of a genus which is the direct descendant of *Orthothetes* of the Devonian and Lower Mississippian; it differs from that genus in the presence of the median septum, seen in *w*; *y, Spiriferina kentuckiensis* (Shum.), a common Carboniferous species; the genus *Spiriferina* differs from *Spirifer* in its punctate shell structure and its median septum; it does not occur below the Mississippian, but extends into the Mesozoic; *z, Chonetes granulifera* Owen. This genus occurs from the Silurian to the close of the Paleozoic, and is common from the middle Devonian up; it is characterized by its concavo-convex form, and the spines along the hinge-line; *aa, Seminula argentea* (Shep.), a spire-bearing, atheroid shell, one of the commonest Carboniferous species; a near realtive is *S. subquadrata* of the Genevieve fauna (see Fig. 237, *l*); *bb, Dielasma bovidens* (Mort.), a common, loop-bearing shell of the Carboniferous; *cc, Rhipidomella pecosi* (Marc.), almost the last representative of the orthid shells which were so abundant in the Ordovician (see Fig. 163); *dd, Spirifer cameratus* Mort., a very characteristic member of this fauna; *ee, Pugnax uta* (Marc.), one of the rhynchonelloid shells; *ff, Lingula umbonata* Cox; the Lingulas persisted from the Cambrian to recent time; *gg, Hustedia mormoni* (Marc.), a small, plicated spire-bearing shell; *hh, Enteletes hemiplicata* (Hall), a peculiar orthid genus found only in the Carboniferous; *ii, Meekella striatocostata* (Cox), a peculiar strophomenoid shell, probably an offshoot from *Derbyia*.

There was a close relation between several American and Russian crinoids, implying intermigration.

Almost the last of the trilobites.—The trilobites which commanded our foremost interest at the opening of the Paleozoic are now almost at the point of disappearance. The last-known genus is *Phillipsia* (Fig. 286, *l*), a modest and beautiful form which retains the symmetry of the ideal type and not a little of its elegance. The extravagances of the Silurian and Devonian forms had vanished, and the last representative of the family had the chaste beauty of its early ancestry.

Other features.—Bryozoans were not uncommon, but the peculiar devices for support illustrated in *Archimedes* and *Lyropora* of the preceding period were abandoned. The protozoans were represented widely by a little foraminiferal shell, *Fusulina secalicus* (Fig. 286, *p*), which had about the size and form of a grain of wheat. Their abundance gives character to the "Fusulina beds" which occur in America, Europe, and Asia. The corals were rare, as might be expected, under the environmental conditions of the time.

As already implied, the fauna had many cosmopolitan features, not a few of its species being common to North America, Europe, Asia, and Australia, and its general facies was the same in all these regions.

CHAPTER XI.

THE PERMIAN PERIOD.[1]

FORMATIONS AND PHYSICAL HISTORY.

After the formations of the Carboniferous group had reached the development already sketched, a general withdrawal of the sea set in, resulting at length (1) in the exposure of those portions of the central and eastern United States that had been covered by it, at least occasionally, and (2) in the restriction of the submerged area in the western part of the country, an area which had been somewhat generally and constantly covered by the sea during the preceding period. With the beginning of the Permian period, the waters which lay upon the continent were partly in the form of lakes and inland seas, and partly connected with the open ocean. Even the areas which the sea overspread at the beginning of the period were largely abandoned by it before the close. As already noted, the deformative movements which finally resulted in the folding of the Appalachian and Ouachita mountains seem to have been inaugurated at about the close of the Carboniferous period, and these movements were doubtless a main cause of the general withdrawal of the sea. These movements appear to have been more profound than those which shifted the epicontinental seas in the preceding periods.

These movements reflected themselves both in the distribution of the Permian formations and in their character. While fresh-water sedimentation continued much as before in some parts of Pennsylvania, West Virginia,[2] Maryland,[3] and Ohio,[4] giving rise to the "Upper Barren Coal Measures"—a name which suggests the close connection of these formations with those which preceded—the Appalachian belt farther south seems not to have been the scene of deposition. The Upper Barren Measures are commonly separated from the Pennsylvanian system on the basis of their plant fossils, rather than because of any stratigraphic break at their base.

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[1] The Permian is often regarded as a part of the Carboniferous. For recent advocacy of this view, see Jour. of Geol., Vol. VII, pp. 321–41.

[2] White, West Virginia Geol. Surv., Vol. II, pp. 100–123.

[3] Martin, Maryland Geol. Surv., Garrett County, p. 144; O'Hara, Allegany County, p. 128, and Prosser, Jour. of Geol., Vol. IX, p. 428.

[4] Prosser, Jour. of Geol., Vol. XI, p. 523.

The Pennsylvania section of the Permian is shown in Fig. 287. Farther north also, in Nova Scotia, New Brunswick, and Prince Edward Island, non-marine Permian strata rest on Carboniferous in such a way as to show that sedimentation was not greatly interrupted, and the two groups are separated on the basis of fossils only. The Permian of Pennsylvania, West Virginia, and the Acadian region seems to represent only the early part of the period, after which these regions appear to have been no longer subject to deposition.

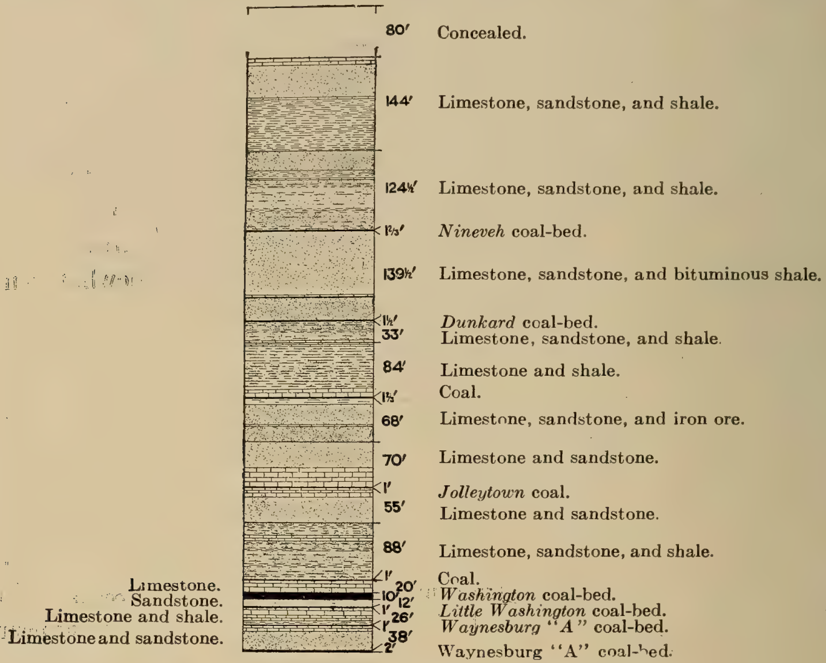
80′ Concealed.
144′ Limestone, sandstone, and shale.
124½′ Limestone, sandstone, and shale.
1⅔′ *Nineveh* coal-bed.
139½′ Limestone, sandstone, and bituminous shale.
1½′ *Dunkard* coal-bed.
33′ Limestone, sandstone, and shale.
84′ Limestone and shale.
1½′ Coal.
68′ Limestone, sandstone, and iron ore.
70′ Limestone and sandstone.
1′ *Jolleytown* coal.
55′ Limestone and sandstone.
88′ Limestone, sandstone, and shale.
1′ Coal.
20′ Limestone.
10′ *Washington* coal-bed.
12′ Sandstone.
1′ *Little Washington* coal-bed.
26′ Limestone and shale.
1′ *Waynesburg "A"* coal-bed.
38′ Limestone and sandstone.
2′ Waynesburg "A" coal-bed.

FIG. 287.—Section of Permian in Pennsylvania.

Permian vertebrate fossils (not marine) have been found in what appears to be the channel of a stream eroded in the Coal Measures in eastern Illinois.[1] Beds thought to be Permian also occur in neighboring parts of Indiana.[2]

West of the Mississippi, the Permian system has a more extensive development, though far less wide-spread than the Pennsylvanian. The Permian strata are best known in Texas, Kansas, and Nebraska, and though the sea was not entirely excluded from this region, it appears, where present, to have been shallow. Locally and temporarily, inland seas were cut off from the ocean. Early in the period the Texan area of sedimentation seems to have been separated from the Kansan by the beginnings of the Ouachita mountains, the uplift of which has been mentioned.

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[1] Case, Jour. Geol., Vol. VIII, pp. 698–729.

[2] Blatchley and Ashley, 22d Ann. Rept. Indiana Dept. of Geol., etc., p. 22, and 23d Ann. Rept., p. 80.

In Kansas[1] and Nebraska[2] the older Permian beds are marine, and though the connection has not been traced, the Permian of these states is probably continued northwestward to Wyoming[3] and South Dakota,[4] for in the Laramie mountains of the former state, and in the Black Hills of the latter, marine Permian beds, with fossils very similar to those of Kansas, are found. The marine Permian of Kansas is overlain by beds containing gypsum and salt, and possessing other features which show that the open sea of the region was succeeded by dissevered remnants, or by salt lakes whose supply of fresh water was exceeded by surface evaporation. Connected with these saline and gypsiferous deposits, and overlying them, are the "Red Beds," sometimes referred to the succeeding Trias; but they appear to be late Permian, in the main at least. This conclusion seems applicable to a large part of the Red Beds east of the mountains, though some are probably Triassic. Some of the Red Beds in western Texas and New Mexico are perhaps later than Permian, and some in Indian Territory and Kansas are possibly the equivalent of portions of the Pennsylvanian system.

The gypsum beds of Iowa may be of Permian age, though there is nothing in their relations to make this certain.[5]

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[1] For an account of the Permian of Kansas see Prosser, Geol. Surv. of Kansas, Vol. II, 1897, pp. 55–97. This article also contains references to the literature concerning the Permian of the western interior. See also papers by the same author on "The Permian and Upper Carboniferous of Southern Kansas," Kans. Univ. Quar., Vol. IV, 1897, p. 149, and on "The Classification of the Upper Paleozoic Rocks of Central Kansas," Jour. Geol., Vol. III, pp. 682–705, and Vol. X, pp. 703–37; Cragin, Permian System of Kansas, Colo. College Studies, Vol. VI, pp. 1–48; Gould, Jour. Geol., Vol. IX, pp. 337–40; and Beede, Am. Geol. Soc., XXVIII, p. 47; and Prosser and Beede, Cottonwood Falls, Kan. folio, U. S. Geol. Surv.

[2] Knight, Jour. Geol., Vol. VII, pp. 357–74, and Barbour, Nebraska Geol. Surv., Vol. I, p. 129.

[3] Knight, Bull. 45, Wyo. Experiment Station, and Jour. Geol., Vol. X, pp. 413–22

[4] Darton, 19th Ann. Rept., U. S. Geol. Surv., Pt. IV.

[5] Wilder, Iowa Geol. Surv., Vol. XII, p. 111.

The Kansas section of the Permian is as follows:[1]

Names of Formations.				Thickness in Feet.	Characteristics.
Cretaceous					
			Unconformity		
Permian System	Cimarron Series.	Kiger Stage	Taloga formation	25–30	Chiefly maroon-colored shales below, with massive red and grayish-white sandstones above; no fossils.
			Day Creek dolomite	1–5	Gray to white; no fossils.
			Red Bluff formation	175–200	Light red sandstone and shale. In Oklahoma contains marine invertebrate fossils.
		Salt Fork Stage.	Dog Creek formation	30 ±	Dull-red, argillaceous shales; laminæ of gypsum in lower part, and ledges of dolomite in the upper; no fossils.
			Cave Creek formation	50	One massive bed of gypsum, or two such beds separated by red clay-shale; caverns abundant.
			Glass Mountain formation	200–225	Fine-grained, bright-red sandstone of varying hardness below, with highly gypsiferous clays above; no fossils.
			Kingfisher formation	800 ±	Saliferous and gypsiferous, prevailingly dull-red or brown shales. Lower part in Oklahoma has vertebrate remains.
	Big Blue Series.	Summer Stage.	Wellington shales	200–450	Mainly bluish gray to slate-colored; occasional beds of dolomite and gypsum.
			Marion formation	400	Mainly buff, thin-bedded limestones, and shales; locally contains beds of gypsum and rock salt; lower portion contains marine fossils.
		Chase Stage.	Winfield formation	20–25	Cherty limestone and shales; marine fossils.
			Doyle shales	60	Varicolored shales; occasional thin beds of soft limestone; marine fossils.
			Fort Riley limestone	40 +	Massive and buff to thin-bedded and shale; marine fossils.
			Florence flint	25	Cherty limestone; marine fossils.
			Matfield shales	60–70	Varicolored shales with some limestone; marine fossils.
			Wreford limestone	35–50	Some portions very cherty; marine fossils.
Pennsylvanian system					

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[1] Prosser, Jour. of Geol., Vol. X, pp. 703–737; Cragin, Colorado College Studies, Vol. VI.

In Texas and the region south of the Ouachita uplift, the system has its greatest development. In the Staked Plains (Llano Estacado) it attains a thickness of 7000 feet. The oldest formation of the system (the *Wichita*) indicates that the critical attitude which characterized the surface farther east during the Pennsylvanian period, now affected Texas, for the beds are partly of marine and partly of fresh-water origin. These beds are succeeded by a formation of limestone (*Clear Fork*), which indicates a submergence sufficient to allow free entrance of the sea. Advance of the sea is further indicated by the fact that the Middle Permian beds overlap the Lower, and rest upon the Pennsylvanian, where no Lower Permian intervenes. The Upper Permian (*Double Mountain*) which follows indicates a reversal of relations, for much of Texas was again cut off from the ocean and converted into an inland sea, or into inland seas, in which the usual phases of deposition under arid conditions took place. Occasional beds of limestone with marine fossils point to occasional incursions of the sea, while the deposits of salt and gypsum point with equal clearness to its absence, or to restricted connections.[1] In the Guadalupe mountains of western Texas, the Permian system has a thickness of 4000 to 5000 feet, and carries faunas unlike those of other regions of North America, but similar to those of the late Paleozoic of Asia.[2]

The Permian sea which overspread part of Texas was perhaps continuous to the west, for a part of the time, as far as the Basin region (Utah); but if so, the continuity of the beds has since been interrupted by erosion. Fig. 288 shows the manner in which the Permian now occurs in some parts of the plateau region of the west. Beds thought to be Permian are known in New Mexico,[3] in northern Arizona,[4] and at other points in the surrounding territory, and in the Wasatch mountains, but not farther west. Throughout much of the area west of the Rocky mountains, the Permian has not generally been differentiated. If it is present, as it doubtless is in some places, it has been classed either with the Carboniferous below or with the Trias above. There is often perfect conformity between the Carboniferous below and the beds classed as Trias above, suggesting the presence of unseparated Permian between. In northern Arizona, however, and in southwestern Colorado,[1] and perhaps at other points, there is an unconformity at the base of the Trias.

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[1] For Permian of Texas, see Cummins, Geol. Surv. of Texas, 2d Ann. Rept., pp. 394–424. Ibid., 4th Ann. Rept., 212–32.

[2] Girty, Am. Jour. Sci., Vol. XIV, 1902, pp. 363–368.

[3] Herrick, Jour. Geol., Vol. VIII, pp. 112–125; and Am. Geol., Vol. XXXI, p. 76.

[4] Walcott, Am. Jour. Sci., Vol. XX, 1880, p. 221.

If the beds tentatively referrred to the Permian be really such, they show that the relatively continuous and clear seas of the Pennsylvanian period in this region had given place to much shallower and less continuous bodies of water, often of more than normal salinity, and that at many points there were interruptions of sedimentation at the close of the Pennsylvanian.

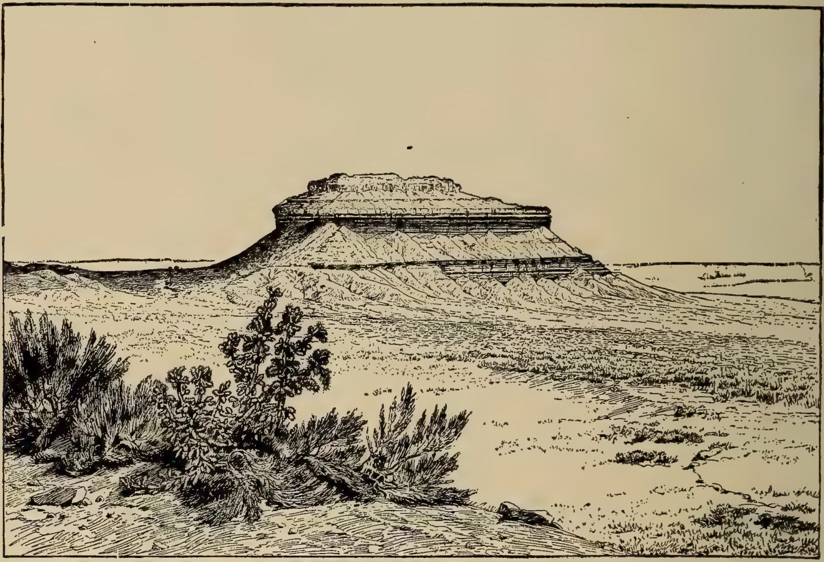

FIG. 288.—A butte composed largely of Permian rock, Northern Arizona (Dutton, U. S. Geol. Surv.

Red Beds, generally classed as Triassic, occur even north of the United States.[2] Their thickness is not great, and they perhaps belong with the Red Beds farther south, most of which are now usually classed as Permian.[3]

The Permian deposits of the far west, as well as some of those of the longitude of Texas and Kansas, are often highly colored, red being the dominant hue. This color so often characterizes formations known to have been made in inclosed basins, that the connection can hardly be fortuitous.

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[1] Cross, unpublished evidence.

[2] Dawson, Bull. Geol. Soc. Am., Vol. XII, p. 74.

[3] Some of the upper Red Beds of central Wyoming are thought to be Triassic (Williston) on the basis of fossils collected by Knight and Branson. The horizon of the Triassic fossils is 550 feet above the base of the Red Beds, and 250 feet below the top.

It is a singular fact, though it may be no more than a coincidence, that certain thin but well-defined layers of clay in the Permian beds of Texas, like certain layers of the Permian in Europe, contain considerable quantities of copper ore. In Europe, however, the copper is confined to a single layer, while in Texas it is distributed through several. This correspondence is perhaps worthy of mention, especially because copper ores are not, on the whole, abundantly distributed, and this is not their usual mode of occurrence.

Thickness.—In the Appalachian region, the Lower Permian beds, sandstone and shale, with thin seams of coal, have a thickness of about 1000 feet. The Upper Permian is wanting. In Kansas the thickness is twice as great, while in Texas it reaches 7000 feet. The Permian system, like the Carboniferous, is thicker in the southern interior than in the Appalachian region.

Correlation.—In the region east of the Mississippi, the Permian is so closely associated with the Coal Measures that the two were formerly classed together. Were this region only considered, this would appear to be the best classification. In the western part of the continent, on the other hand, the differentiation of the Permian from the Carboniferous is more distinct, and its relation with the Trias is generally close. In the Texas-Kansan region, for example, the relations of the Permian to the Trias, if the beds referred to the Trias are really such, are so close as to have caused the frequent reference of the upper part of the former to the latter. Perhaps the Permian period is best looked upon as a transition period from the Carboniferous to the Trias, and so from the Paleozoic to the Mesozoic. According to this view, its close relationship to the underlying system in some places, and to the overlying system in others, is natural.

THE FOREIGN PERMIAN.

Europe.

In Europe, as in America, the Carboniferous period was brought to a close by very considerable changes, for much of the area which had been receiving deposits during that period was exposed to erosion at its close. Subsequently, through further changes, much of the same surface was again brought into a position for renewed deposition, partly from fresh and partly from salt waters. The Permian system thus formed is on the whole much more distinct from the Carboniferous than the Permian of the eastern part of North America, and is much better known.

During this period Europe was divided into two somewhat distinct provinces, a division which began to show itself in the later part of the Carboniferous period, when the Upper Carboniferous limestone was in process of deposition in southern and eastern Europe. Corresponding in a general way with these two provinces, the Permian has two somewhat different phases known as the *Dyas* and the *Permian* respectively. The former name had its origin in the twofold division of the system, and the latter came from a province of Russia where the formation is well developed. In England, both phases of the system are represented, the Dyas in the east and the Permian in the west,[1] and in the Baltic province of Russia, the Dyas phase is found. In general, the Permian system is somewhat more wide-spread than the Upper Carboniferous which it overlies, often unconformably, and which it overlaps in various directions.

Except in Russia, where its extent is great, the Permian appears at the surface around mountain cores and in narrow strips only; but from the positions of these outcrops, it is inferred that the formation, is in reality widespread beneath younger beds.

Lower Permian.—Where the Dyas phase of the formation is developed as generally in western and central Europe, the Lower Permian (*Rothliegende*) consists of a series of fragmental beds made up of shale, sandstone, conglomerate and breccia, with which there is associated a large amount of igneous rock, now in the form of lava-sheets, now in the form of dikes, and now in the form of volcanic material. The amount of igneous matter is so great (especially in Scotland, Bavaria, and southern France[2]) and is so widely distributed (occurring also in England, the Vosges and Thüringerwald mountains, the Alps, etc.) that it is to be looked upon as rather characteristic of the Lower Permian.

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[1] Geikie's Text-book of Geology, p. 1070.

[2] Ibid., pp. 1070, 1073, 1075.

The Rothliegende is often unconformable on the Carboniferous. The character of the formations and of their fossils is such as to show that much of the sediment was accumulated in inland seas, and in salt and fresh lakes. Gypsum, salt, and a meagre fauna of dwarfed and stunted species, some of which are of certain marine types,[1] are among the distinctive marks of the series. To these inland areas of sedimentation the sea sometimes had access, as the nature of the formations and their fossils show. It may have had limited access, even while the salt and gypsum beds were being deposited. There were lakes of fresh water also in which sediments gathered, and in these parts of the system, fossils of terrestrial as well as lacustrine life are found. Even in some of the Permian limestones (as in France) fresh-water fossils only are found. The shallow-water or subaërial origin of much of the Permian is shown by the sun-cracks, rain-pittings, ripple-marks, etc. Tracks of terrestrial and amphibious animals, impressed in the muds and sands while they were accumulating, are also found.

In keeping with the conditions of its origin, the Rothliegende often contains beds of coal. This is the case in France, where one coal-bed attains a thickness of 82 feet;[2] in Saxony, in the Harz, Schwarzwald and Thüringerwald mountains; and in Bohemia where the valuable coal-beds occur in the Rothliegende more than in the Carboniferous.[3] In the region of the Ural mountains, too, the Lower Permian beds are non-marine and coal-bearing.[4]

Especial interest attaches to the conglomerates and breccias of the system because of their likeness to glacial drift.[5] This likeness is found not only in the presence of large bowlders, but in their character and in the matrix in which they are set. Furthermore, the stones have now and then been observed (Midlands and west of England) to carry marks which have been thought to be glacial striæ. This origin of the marks, however, has been called into question. The conglomerate is wide-spread, and in some cases contains bowlders which have been transported considerable distances.

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[1] Kayser, op. cit., p. 226.

[2] Idem, p. 253.

[3] Idem, p. 230–238.

[4] De Lapparent, Traité de Géologie, p. 969.

[5] Ramsay, Q. J. G. S., 1855, p. 185; and Geikie, op. cit., p. 1064. There seems to be some question as to whether these formations should be referred to the Carboniferous or the Permian.

The Lower Permian strata of the Dyas phase are often red, as suggested by their German name (*Rothliegende*). Strata of the same age constitute at least a part of the "New Red Sandstone" of Great Britain. As a matter of fact, however, while the colors of this formation are usually striking, other colors than red are often found. The fact that the red color is characteristic of the same system in much of America has been noted.

In contrast with the Rothliegende, the Lower Permian of much of southern Europe is of marine origin, and is generally conformable on the Carboniferous. Non-marine Permian beds are, however, found as far south as the Alps, and even into Italy. On account of its fossils and its relations to the Carboniferous, the Lower Permian of southern Europe has been thought to be older than the Rothliegende.[1] It is widely distributed, occurring in the Alps, Italy, Sicily, the Pyrennees and in the Balkans.

The typical Permian phase of the system underlies the larger part of Russia (in Europe), and appears at the surface over a large area in the southeastern part of that country. It is generally conformable on the underlying Carboniferous. Its lower part is made up largely of clastic beds bearing non-marine fossils. Some beds, however, contain the shells of marine species. The Lower Permian extends to Nova Zemla on the north, and to the steppes of Kirghiz in Asiatic Russia, on the east.[2]

The Upper Permian.—The Upper Permian of western and central Europe (the *Zechstein* of Germany) is unlike the Lower in several important respects. It contains much more limestone and dolomite, but neither coal, igneous rock, nor, except at its very base, conglomerate. Such characteristic marine fossils as cephalopods and corals are generally absent,[3] and from the stunted aspect of the fossils, and from the association of the dolomite with gypsum, salt, etc., it is thought that the limestone and dolomite may be largely chemical precipitates. Some parts of the Upper Permian are, however, of marine origin. In southern Germany, Bohemia, and France, the Zechstein has little representation.[1]

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[1] De Lapparent, Traité de Géologie, p. 985.

[2] Kayser, op. cit., pp. 253–255.

[3] Idem, p. 226.

The Upper Permian of western Europe is remarkable for the fact that certain thin beds of peculiar character are exceptionally persistent over wide areas. Thus at its very base, there is a thin but persistent bed of conglomerate (perhaps a basal conglomerate), and a little higher in the series there is a thin layer, rarely reaching a thickness of as much as five meters, and often less than one, which, over very considerable areas, carries abundant ores of various metals, among which copper is prominent. It also carries abundant fish remains, and is rich in bitumen. This layer (*Kupferschiefer*), thin as it is, has long been worked in Germany, now chiefly about Mansfield, especially for the copper. The ore occurs in small grains, distributed through the sedimentary bed. The grade of the ore is rather low, but it is

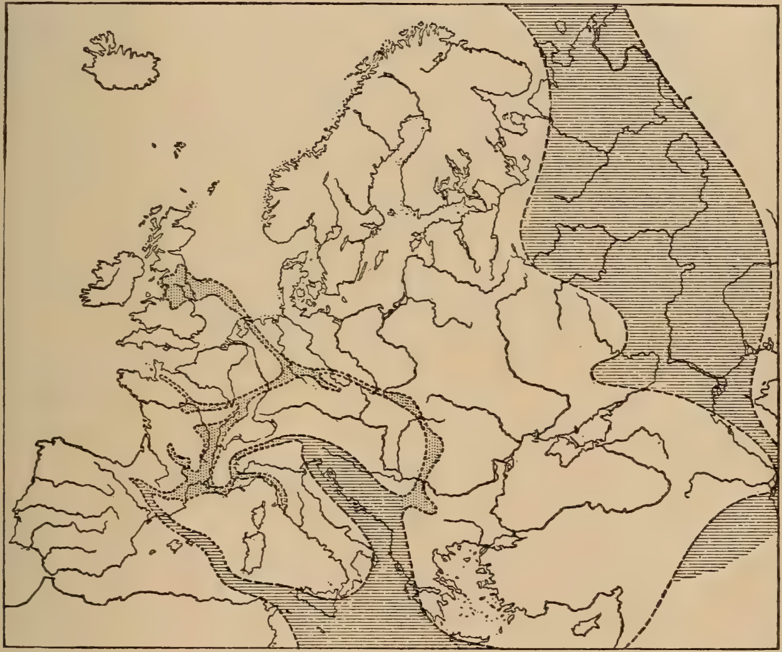

FIG. 289.—Sketch map of Europe showing the areas of deposition in the early part of the Permian period. The lines indicate areas of marine sedimentation, and the dots areas of non-marine sedimentation. (After De Lapparent.)

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[1] Kayser, op. cit., p. 225.

easily worked. The origin of the copper has been referred to submarine mineral springs, which have even been supposed to have poisoned the waters and so to have destroyed the organisms in them, the decay of whose remains gave rise to precipitating agents. More in the natural order of things, the ore has been referred to the leaching of igneous and other rocks by surface-waters tributary to the basin in which the deposit took place, the precipitation of the ore being assigned to the organic agencies common to inhabited waters. Such an explanation gains in plausibility from the fact that the area where the copper occurs appears to have been a somewhat enclosed basin, rather than the open sea. The ores are best developed in the vicinity of faults, which indicates that they are, in part at least, of secondary origin. The singular fact that the Permian of Texas, as well as that of Europe, contains copper ores in similar relations, has been referred to.

The Upper Permian of central and western Europe contains the thickest salt-beds known in any part of the earth. Near Berlin, one of these salt-beds has been penetrated to the depth of about 4000 feet, and its bottom has not been reached. In addition to common salt, salts of potash and magnesium were locally (Stassfurt) deposited in such quantity as to be commercially valuable. The world's supply of potassium salts, with the exception of saltpetre, comes from these beds.[1] Like the rock salt, these salts probably represent precipitates from the waters of inclosed basins under special conditions.

The Upper Permian of eastern Europe is largely of non-marine origin, as shown by the salt, gypsum, etc., which it contains. Marine fossils are, however, not wanting,—are indeed rather more common than in the Zechstein farther west. Over wide areas, the beds are impregnated with copper. The flora is of a type (*Glossopteris*) not well developed elsewhere in Europe, but prevalent in the Permian or Permo-Carboniferous of Africa and Australia.[2].

The Permian system is present in Spitzbergen, where it is wholly marine. The fossils are more closely allied to those of the north Pacific than to those of Russia and India, as if there were a boreal marine province.[3]

General.—On the whole, the Permian system of Europe possesses features which show that the general attitude of the continent was comparable to that of North America at the same time. In both continents there are beds which accumulated in fresh water; in both, beds which were laid down in salt lakes or inland seas; and in both, beds deposited on the floor of epicontinental seas. Great areas in both continents seem to have maintained a halting attitude near the critical level during much of the period, while in both continents there were considerable areas of dry land.

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[1] Kayser, Geologische Formationskunde, p. 250.

[2] Amalitzky, Review of article by, Geol. Mag., 1901, p. 231

[3] De Lapparent, p. 986.

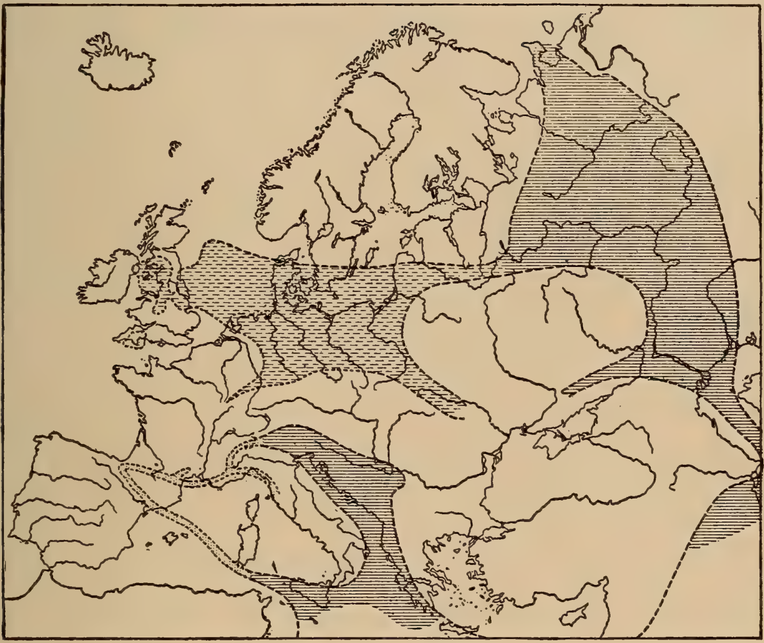

Fig. 290.—Sketch map of Europe during the later part of the Permian period. The lines indicate areas of marine deposition, the broken lines areas of lagoon deposits; and the dots, areas of continental (land) deposition. (After De Lapparent.)

The differences between the continents are not less instructive than the likenesses. The Permian period was distinguished in Europe by great igneous activity, while that of America, though marked by the growth of mountains, was essentially non-igneous. The Permian system of Europe seems to be more closely allied, stratigraphically, with the Trias than with the Carboniferous, and while the same is true of the western part of North America, the opposite is true for the eastern part.

In other parts of the world the Permian is widely developed. In countries about the Indian Ocean, including South Asia, Australia, and southern Africa, there is usually a less distinct break between the Carboniferous and the Triassic systems than in Europe, and, locally at least, the Permian seems to completely bridge the interval.

Australia.—In South Australia, above a series of Coal Measures the plants of which are of the normal Carboniferous types, there is a series of marine beds alternating with beds which contain land plants unlike those of the Coal Measures below. Considerable beds of coal are also included in the series. Interstratified with these marine strata and coal seams there are considerable beds of conglomerate of distinctive glacial type (Fig. 291). Some of the bowlders of the conglomerate are striated in such a way as to leave no doubt as to their glacier origin. Furthermore, the substratum on which the bowlder beds rest has been repeatedly observed to be grooved and polished, like *roches moutonnées*, and the direction in which the ice moved has been determined in more than one locality. Unwilling as geologists were to believe that there was a glacial period at this early stage of the earth's history, the evidence now in hand is overwhelming, and a glacial period in Australia in the late Carboniferous or Permian period must be regarded as a demonstrated fact.[1]

The number of well-defined bowlder beds is in places (Bacchus Marsh District, Victoria) not less than nine or ten, and some of them have a thickness of fully 200 feet. The marine beds with which they are intercalated have an aggregate thickness of 2000 feet or more,[2] and 30 to 40 feet of coal are included between the highest and lowest of the bowlder beds. The recurrence of the bowlder beds points to the repeated recurrence of glacial conditions, and the great thickness both of clastic beds and of the included coal point to the great duration of the period through which the several glacial epochs were distributed.

These remarkable phenomena are not local. Counting Tasmania, where glacial deposits are also found, the Paleozoic glaciation of Australia had a known range of nearly 22° in latitude (42° in Tas-

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[1] W. E. David, Q. J. G. S., Vol. LII, 1896, p. 289–301. "Glacial Action in Australia in Permo-Carboniferous Time." Contains also references to all the literature on the subject.

[2] Geikie gives 3500 feet, op. cit., p. 1060.

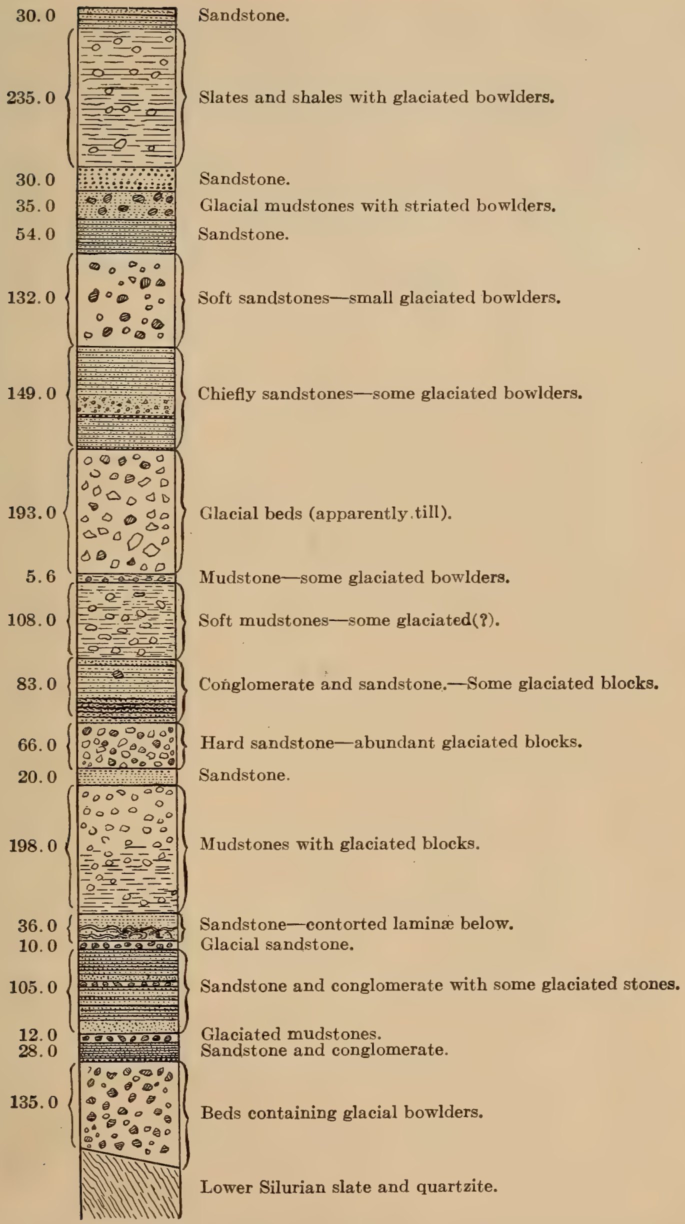
30.0 Sandstone.
235.0 Slates and shales with glaciated bowlders.
30.0 Sandstone.
35.0 Glacial mudstones with striated bowlders.
54.0 Sandstone.
132.0 Soft sandstones—small glaciated bowlders.
149.0 Chiefly sandstones—some glaciated bowlders.
193.0 Glacial beds (apparently till).
5.6 Mudstone—some glaciated bowlders.
108.0 Soft mudstones—some glaciated(?).
83.0 Conglomerate and sandstone.—Some glaciated blocks.
66.0 Hard sandstone—abundant glaciated blocks.
20.0 Sandstone.
198.0 Mudstones with glaciated blocks.
36.0 Sandstone—contorted laminæ below.
10.0 Glacial sandstone.
105.0 Sandstone and conglomerate with some glaciated stones.
12.0 Glaciated mudstones.
28.0 Sandstone and conglomerate.
135.0 Beds containing glacial bowlders.
Lower Silurian slate and quartzite.

Fig. 291.—Section showing the position and relations of the glacial beds in Australia (David.)

mania to 20° 30′ in Queensland), and about 35° in longitude (west from 137° 30′), though it is not known, nor perhaps probable, that all the area within these limits was glaciated. On the other hand, it is not to be understood that the phenomena here described are restricted to high altitudes; rather are they known chiefly at low levels, descending in some places nearly to the sea. The altitude of this region is not only low now, but it was probably low during glaciation, as shown by the relation of the glacial deposits to the marine beds. Whatever the difficulties in the way of its explanation, therefore, the fact of a long period, during which glacial conditions recurred many times must be accepted.

The marine beds associated with the glacial deposits seem to match approximately those of the Carboniferous period elsewhere, but the plants of the associated coal show none of the most characteristic types of the Carboniferous beds as developed in Europe and America. Rather do they present the general facies of the Triassic flora. On the other hand, Permian fish remains are found above all the bowlder beds, suggesting that the glacial conditions were over before the end of the Permian, though in the same beds which contain fish remains, some have thought to see evidence of ice action. The glacial character of these later beds has, however, not been proven. In any case they are younger than the certainly glacial beds below. The testimony of the plant fossils is therefore that the period of glaciation was late Permian or early Triassic; that of the marine fossils that it was late Carboniferous or early Permian. The better view, probably, is to regard the glacial beds as the base of the Permian.

In some parts of Victoria, the Permian rests unconformably on the Lower Carboniferous. The glacial series is succeeded by coal-bearing beds, and these by the Triassic system. The upper part of the system is coal-bearing also in New South Wales. The thickness of the Permian in this region is some 13,000 feet.[1]

India.—Overlying crystalline schists of great age, there is in the central part of the peninsula of India a system of rocks known as the Gondwána system. This system is made up of several divisions, the lowest of which (the Talchir) is formed in considerable part of glacial conglomerate, the bowlders of which are sometimes as much as four meters in diameter. Locally, the glacial series (the glacial beds and the formations interstratified with them) has a thickness of about 2000 feet.[1] The few plant fossils associated with this conglomerate are like those associated with the coal-seams of the glacial series in Australia. The age of these conglomerates is further indicated by the fact that they are overlain by the Fusulina limestone (late Carboniferous or Permian) comparable to that of Europe. Coal-beds, regarded as Middle Permian (the important coal-beds of India), also occur above the Talchir conglomerates in the Gondwána system, thus seeming to make them either late Carboniferous or early Permian.

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[1] Kayser Geologische Formationskunde, p. 265.

The character of the Talchir conglomerates, especially when studied in connection with the bed on which they lie, may fairly be regarded as demonstrating their glacial origin; for not only are the bowlders glacially striated, but the surface beneath the conglomerate, like the bed of the similar deposits in Australia, is also polished and striated.[2]

The glacial Paleozoic formations in India are in some respects even more remarkable than those of Australia, for they reach below the latitude of 18°, and are, therefore, several degrees within the Tropic of Cancer; not only this, but they occur at low levels, descending in places nearly to the level of the sea.

Conglomerates which appear to be of glacial origin are not limited to the Talchir formation of the peninsula. Similar formations, believed to be of the same age, appear in the Salt Range of India (Lat. 32°), in the central Himalayas, in Cashmere, and Afghanistan.

In the Salt Range, a marine Permian formation overlies the glacial series. Marine Permian is also known in northern Persia, Armenia, the central Himalayas, Tibet, central India, Timor, Yünnan, Nanking, and elsewhere.

South Africa.[3]—In South Africa there is a series of beds found in various parts of Cape Colony, Natal, Zululand, the Orange River State, and the Transvaal, which possess the same general characteristics as those of Australia and India. Here there are conglomerate beds (the Dwyka formation) some of which are glacial, and some of which were probably deposited in water, in which bergs were floating.[1] These conglomerates are associated with strata (the Ecca shales) which are referred to the Permian system. Many of the bowlders of these conglomerates are striated, and at the same time the bed on which the glacial conglomerate rests shows indisputable marks of ice action in many places (Figs. 292 and 292*a*). The glacial beds are believed to have extended as far north as 26° 40′ in the Transvaal. The glacial and associated beds have great thickness (1200 feet) in Cape Colony.

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[1] Kayser, op. cit., p. 262.

[2] Oldham, Geology of India, 2d ed., 1893.

[3] For an excellent account of the Paleozoic glacial phenomena of these several regions, see C. D. White, Carboniferous Glaciation in the Southern and Eastern Hemispheres, Am. Geol., 1889, Vol. XIII, pp. 299–332. For a later account of the glacial beds, see footnote, p. 636. See also Geol. Cape Colony, Rogers, 1905, pp. 147–179.

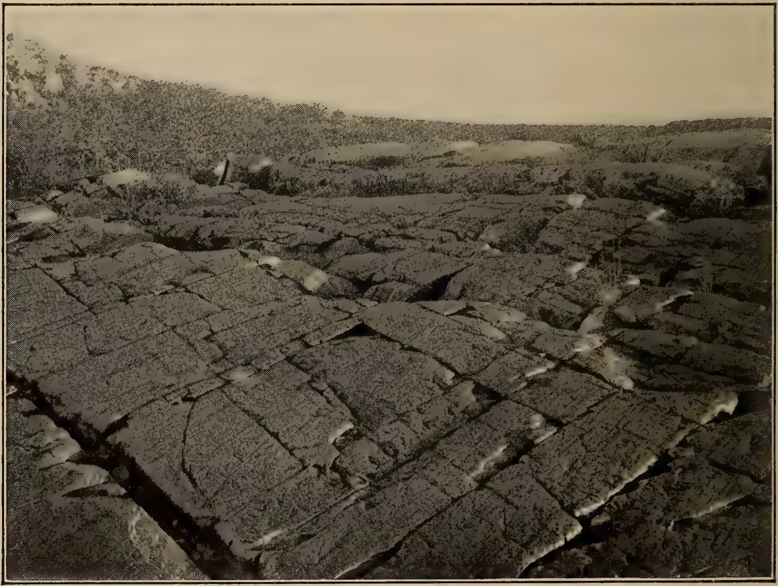

FIG. 292.—Glaciated quartzite beneath the glacial conglomerate of South Africa. Near Prieska. The rock surface shows glacial striæ. (Schwarz.)

Above the Ecca shales, which are thought to be glacio-fluvial or glacio-lacustrine,[2] is the coal-bearing Beaufort series with Glossopteris flora and abundant reptilian remains.[3]

The known Permo-Carboniferous glaciation of Australia, India, and Africa is found in two zones, the one north and the other south of the equator. In neither zone have the limits of glaciation been accurately determined, but in the former it is known to have extended from latitude 18° to about 35°, and probably still farther north, while in the latter it is known to have extended from latitude 21° to 35°. In an equatorial zone about 40° in width, glaciation has not been discovered. The glaciation of these various countries has a range of about 130° in longitude. Glacial conditions must, therefore, have prevailed over an area, or at least about the borders of an area many times as large as that covered by ice in the northern hemisphere during the Pleistocene glacial period.

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[1] Scottish Geog. Mag., Vol. XVII, 1901, p. 57; and Trans. Phil. Soc. of S. Africa, Vol. XI, 1900, p. 113.

[2] Molengraaff, Bull. de la Soc. Geol. de France, 1901, p. 79.

[3] Broom, Geol. of Cape Colony, pp. 228-244.

The marked likeness of the floras associated with the glacial deposits throughout these three continents is believed to be evidence that there was land connection between them at the time of the glaciation. The horizons to which the Carboniferous types of plants are restricted, especially in Australia, have been thought to represent a lesser interval of time than that occupied in the deposition of the Carboniferous beds of Europe and America. Partly on this ground, the plant-bearing beds associated with the glacial deposits in Australia, and containing the Glossopteris flora, have been believed to represent the later part of the Carboniferous period; and if so, they indicate that the plant-life of this region advanced more rapidly than that of Europe and

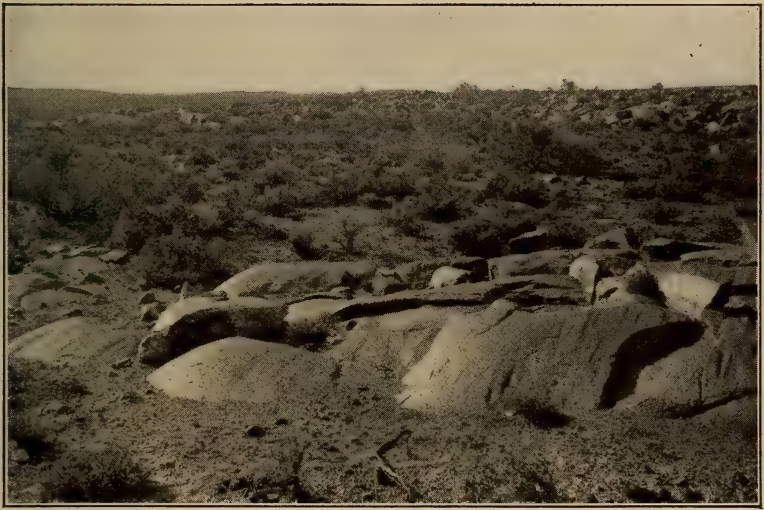

Fig. 292*a*.—North slopes of roches moutonnées. Near Prieska, South Africa. The rock surface shows glacial striæ. (Schwarz.)

America, for the Glossopteris flora is allied to the Triassic flora of other regions. Since in all these regions the Glossopteris flora antedated or attended the glacial beds, it has been thought to be the flora of a cooler climate, and that this climate was the beginning of the change which culminated in glaciation. As already indicated, the Carboniferous and Permian are not sharply differentiated in these countries. On the whole, the general relations seem to suggest that the beds containing the Glossopteris flora and the glacial beds were contemporaneous with the early Permian of other regions, rather than with the Carboniferous proper. If this be true, the culmination of the later Paleozoic glaciation was in the early Permian. In the later part of this period there seems to have been an advance of the sea on the land, both in Europe and Asia (Salt Range of India).

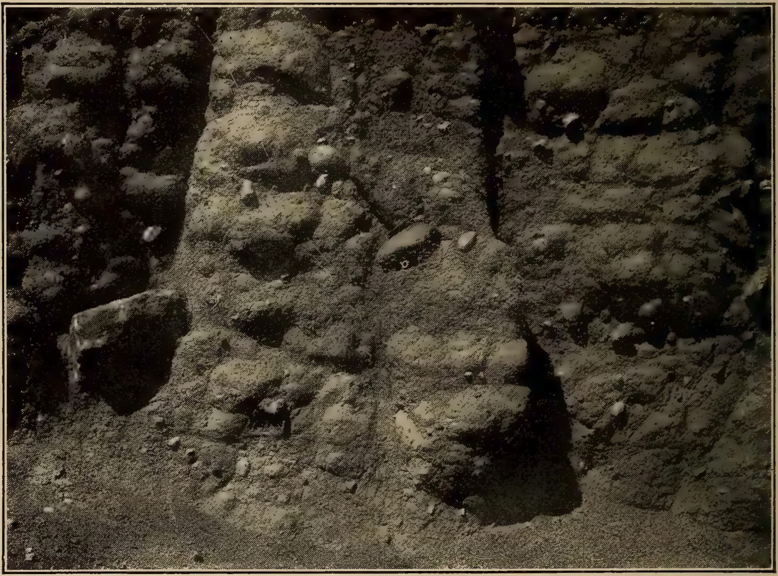

Fig. 293.—Section of glacial conglomerate near Prieska. The conglomerate is overlain by Triassic shale. (Schwarz.)

South America.—Rocks like those of the countries about the Indian ocean are also known in Argentina and the southern part of Brazil. In the latter situation, conglomerates of glacial aspect have long been known. Their glacial character has now (1906) been proved by I. C.

White.[1] Coal-bearing beds with the Glossopteris flora lie unconformably on older formations, and conformably below the Trias.[2]

CLOSE OF THE PALEOZOIC ERA.[3]

The close of the Paleozoic era was marked by much more considerable geographic changes than the close of any period since the Algonkian. These changes may be said to have been in progress during the Permian period rather than to have occurred at its close. The changes in the relations of land and water, and the deformation of strata mentioned in connection with the close of the Carboniferous period (p. 584), probably continued during the Permian.

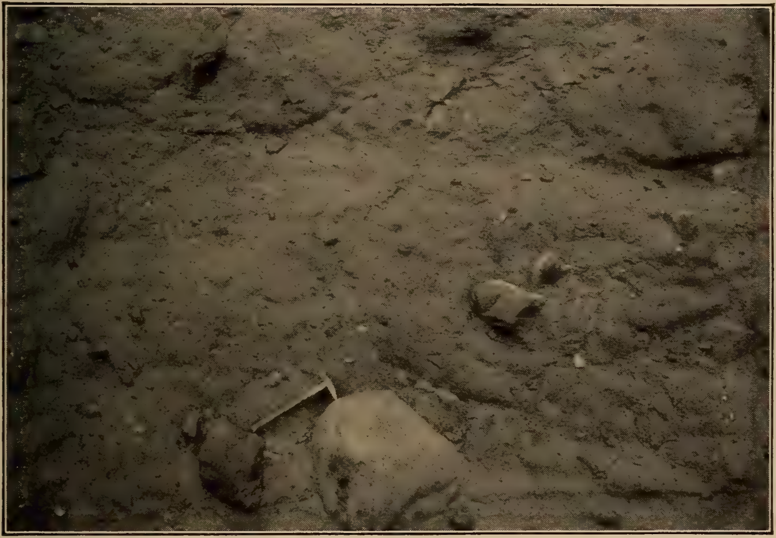

FIG. 294.—Section of glacial conglomerate (cemented till) near Prieska, South Africa. (Schwarz.)

It will be remembered that there was a considerable withdrawal of the sea from North America at the close of the Ordovician, converting large areas which had been submerged during the Cambrian and Ordovician periods into land; but as the Silurian period progressed, the sea gradually crept back over much of the area from which it had temporarily withdrawn. Of the larger part of this area the sea retained possession through the later part of the Silurian and the Devonian periods, and during the Mississippian it was greatly extended.

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[1] Geol. Soc. Am., Dec. '06.

[2] Kayser, Geologische Formationskunde, p. 265. This author states, pp. 227 and 265, that glacial beds occur in South America.

[3] Smith, J. P., Jour. Geol., Vol. IX, pp. 512–21.

In the Coal Measures period great areas were converted into marshes, and still later in the period, or at its close, a wide-spread withdrawal of the sea made most of the area of the United States east of the 96th meridian, land. The geographic changes may be best appreciated by comparing the maps on pages 497 and 545. The movements which resulted in these changes were probably slow, and for most of the area not notably deformative.

The great geographic changes which had been accomplished, or far advanced, by the close of the Paleozoic, were (1) the development of the Appalachian mountain system at the western border of Appalachia; (2) the deformation of the surface of Appalachia; (3) the development of the Ouachita mountains; (4) the final conversion of the larger part of the area between the Great Plains and Appalachia from an area of deposition to an area of erosion; and (5) the restriction at the west of the area of sedimentation in the western interior.

Such extensive geographic changes, involving the conversion of such great areas from sea bottom into land, must have caused profound changes in the circulation of water, in climate, and in the distribution of terrestrial and marine life.

THE LIFE OF THE PERMIAN.

The life of the Permian can carry its full meaning and receive its full interpretation only when put into association with the extraordinary physical conditions which formed its environment. These were the most remarkable in the post-Cambrian history of the earth. Between them and the life there must have been reactions and adaptations of the utmost significance, if we could surely read them. At no period, save our own, were the phenomena so pronounced, and hence, with little doubt, so rich in possible instruction as to the adaptation of life to extreme conditions. Their teachings have been less eagerly sought and less freely received than they merit, because of prevalent preconceptions as to what *must* have been the state of the atmosphere and the type of life, arising from a single unquestioned hypothesis of the early state of the earth and its necessary sequences. If alternative views on this fundamental subject are entertained, the psychological conditions will be more felicitous for following to their legitimate conclusions the extraordinary facts of this critical period.

Because the physical conditions were so pronounced in the salient features of glaciation and aridity, certain questions relative to the life at once arise: (1) Was it possessed of such powers of adaptation that it met its extraordinary environment by accommodating itself to it; or (2) was it destroyed co-extensively with the changes in environment; or (3) did it elude the adverse conditions by shifting from one area to another as the adverse conditions shifted (hypothetically); or (4) did its composite experience embrace all these, and if so, what measure of each?

The impoverishment of life.—There is no question but that there was a great reduction in the amount of life. In the earlier days of geology, it was commonly held that a complete destruction of all living things on the face of the earth attended this closing period of the Paleozoic era, and that a re-creation followed; for in the state of knowledge of that time, no Paleozoic form was known to occur in the following era. Had it then been known that glaciation pressed upon the borders of the tropics on either side, in the far Orient, and that intense aridity dominated large areas elsewhere, it would have added great strength to the conviction of a universal catastrophe to life. With the progress of investigation, however, no small relief from the adverse data has been found in the discovery that some forms bridged the interval, and in the additional grounds for belief that many others underwent modifications which enabled them to pass it as new types, and in the accumulating evidences that the succession of life was unbroken, though greatly modified. Progressive investigation is still bringing forth more and more evidence of this kind, and reducing the disastrous implications of the record. Not only this, but wide study brings into view the compensating effects of the strenuous conditions in calling into play the latent powers of adaptation and of resistance of the organisms, and in producing new forms of life. Notwithstanding all this, it yet appears that the life of the period was greatly impoverished. A census made a few years ago gave the known animal species of the Carboniferous period as 10,000, while those of the Permian period were only 300, or three per cent. A census to-day would probably improve the Permian ratio notably, but the contrast would still be great.

I. The Plant Life.

Change in the flora.—The change of the vegetation from the Carboniferous to the Permian in America was rather marked, but not, at the outset, radical. There was a progressive evolution as the period advanced. Fontaine and White[1] have shown that in West Virginia and Pennsylvania the lowest beds referred to the Permian, with a record of 107 species, contain 22 species found also in the Coal Measures below, and 28 found in the Permian of Europe. Of the 22 species found in the Coal Measures, 16 are common to the Permian of Europe, so that only 6 species which may be regarded as distinctive of the Coal Measures rise into the base of the Permian, and, with one exception, all the Coal Measures' species had disappeared before the second fossiliferous horizon of the Permian series is reached. This implies that a rather profound change was in progress, but that it was not altogether abrupt. In some portions of Europe the change seems to have been somewhat more gradual, and in others, where unconformity occurs, somewhat more abrupt. In Nova Scotia and Texas the transition seems to have been gradual, rather than abrupt. Respecting the change in the southern hemisphere, opinion must be held in some reserve until final correlations are established; but if the glacial bowlder beds be taken as marking the base of the Permian, a transition seems to have been in progress somewhat earlier, and to have become profound as the natural result of the glacial invasions, which were followed by a new flora.

Only a small part of the total floral change of the Permian appears in the American record, as now known; but the nature of the early change is distinctly indicated. The *Lepidodendron* disappeared and the *Sigillaria* became very rare. The *Calamites* were greatly reduced in importance, and *Equisetites,* their successors in line, appeared, while the *Schizoneura* branch of the family also was represented. *Sphenophyllum* held on into the period chiefly by new species. While some of the more persistent genera of Coal Measure ferns or *Cycadofilices* were represented by new species, the majority disappeared, and new genera took their places, *Callipteris, Tæniopteris* and *Cymoglossa* being especially significant of the new order of things. Of the older genera, *Pecopteris* was especially prolific in species, and *Sphenopteris* and *Goniopteris* were well represented. Just how many of these frond-genera were true ferns and how many *Cycadofilices* remains to be determined, but we are warranted in noting the singular fact that the fern-stock survived changes with more success than most of its contemporaries. The *Cordaites* continued, and initial forms of the ginkgos appeared in *Saportea* and *Baiera* and gave a Mesozoic forecast to the flora.

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[1] Second Geol. Surv. Penn., Permian Flora, 1880.

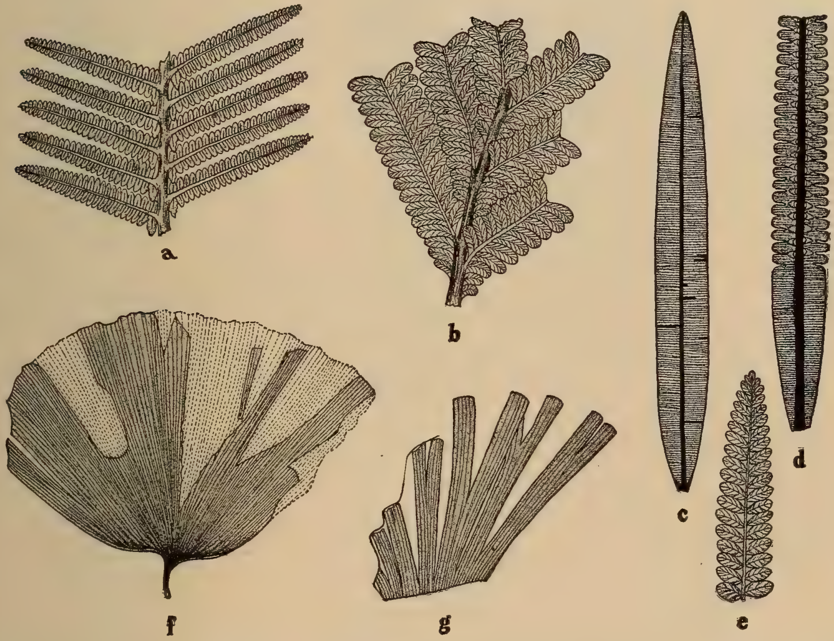

FIG. 295.—PERMIAN FLORA OF AMERICA: *a, Pecopteris tenuinervis* Fontaine and White; *b, Callipteris conferta* Bgt.; *c*, sterile frond of *Tæniopteris newberriana* Fontaine and White; *d, T. newberriana*, basal part of a fructified frond; *e, Cymoglossa obtusifolia* Fontaine and White; *f, Saportea salisburioides* Fontaine and White; *g, Baiera virginiana* Fontaine and White.

In Europe, most of the above forms appeared rather sparsely at the opening of the period, and gradually increased in prevalence, while the residual Carboniferous species declined. The general aspect of the flora remained, however, that of poverty. Two new types of much interest came in and became characteristic, *Walchia* and *Voltzia*. *Walchia* (Fig. 297) resembled an Araucarian conifer in its foliage, but its seed organs were apparently different. While conifers have been reported from earlier systems on the doubtful basis of woody tissue, *Walchia* may probably be safely regarded as representing them.

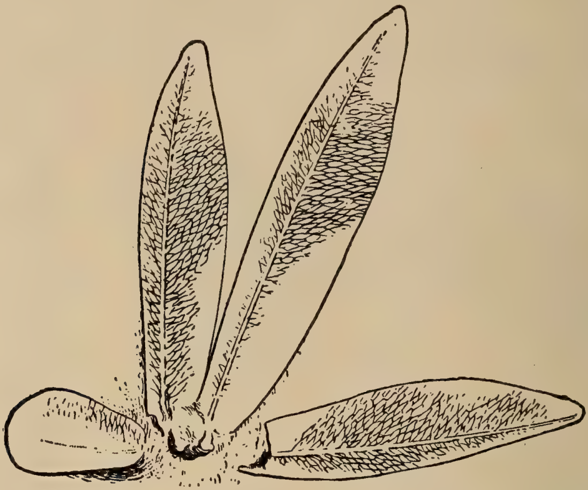

Fig. 296.—A verticel of leaves of Glossopteris. ×2. (After Etheridge.)

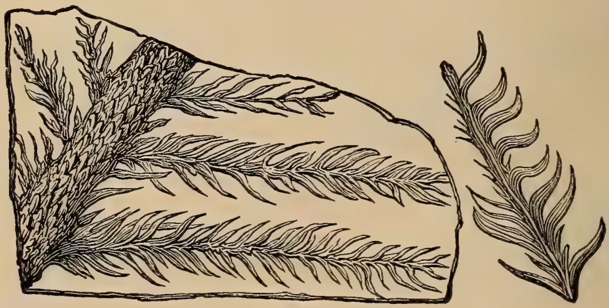

Fig. 297.—*Walchia piniformis*, a Permian conifer of Europe.

It had small bract-like leaves closely and thickly attached to the limbs, giving it a scrawny appearance. *Voltzia* (Fig. 298, *h*) is interesting as a supposed forerunner of the group (*Cryptomeria*) to which the giant sequoia and the bald cypress belong. The abbreviated leaves and pauperitic aspect of both *Walchia* and *Voltzia* will be noted.

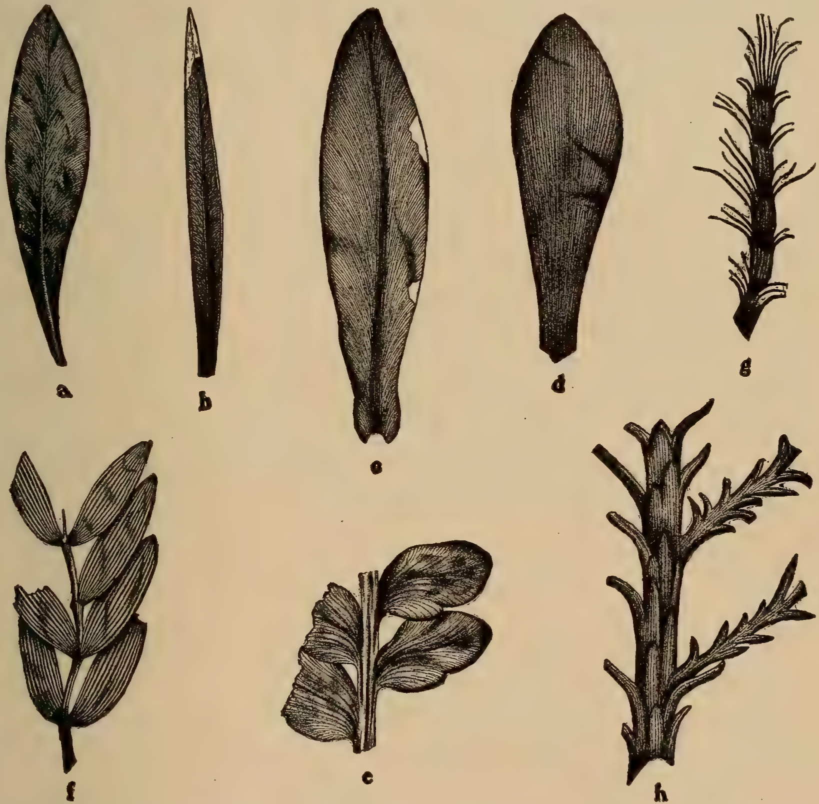

Fig. 298.—Representative types of the Glossopteris Flora: *a*, *Glossopteris communis*, Fstm.; *b*, *G. angustifolia*, Bgt.; *c*, *Gangamopteris cyclopteroides*, Fstm.; *d*, *Noeggerathiopsis hislop*, Bunb.; *e*, *Neuropteris valida*, Fstm.; *f*, *Schizoneura gondwanensis*, Fstm.; *g*, *Phyllotheca indica*, Bunb.; *h*, *Voltzia heterophylla*, Bgt.

The Glossopteris flora.—The most remarkable vegetal event of the period was the evolution of the *Glossopteris* (tongue-fern) flora in the southern hemisphere, and its migration into the northern. The representative members of this flora were the ferns *Glossopteris*, *Gan-*

gamopteris, *Noeggerathiopsis*, and *Neuropteris*, the equisetales *Phyllotheca* and *Schizoneura*, and the conifer *Voltzia* (Fig. 298, *a-h*), the first two being eminently characteristic. The peculiar expression of the group will at once be recognized, especially the simplicity of the outlines of the fern leaves, and their contrast to the usual dissected forms, as also the pauperate aspect of the *Voltzia*. These give support to the view that this flora was evolved to meet the adversities of climate which prevailed in and about the glaciated regions. While the fossils of this flora do not actually appear in the glacial beds themselves, they are found in tne interglacial deposits, and in those that lie immediately above the upper glacial beds. Developed thus amid adverse surroundings, if not directly under adverse conditions, the flora not only took on a resistant aspect in simple outlines and compact forms, but soon gave evidence of its vitality by spreading northward into east Africa and Asia, and then Europe.[1] It reached northern Russia in the latter part of the Permian period (Amalitzky), where it was associated with *Callipteris* and other forms typical of the European Permian flora. It is also found in Brazil and Argentina. Its vitality is further shown in that its descendents became a dominant feature in the Mesozoic floras that followed.

II. The Land Animals.

The Amphibians.—Relatively, the amphibians reached their most declared supremacy in the latter portion of the Carboniferous period, and they may have been then actually at their numerical climax, for the conditions were apparently extremely favorable for them. They continued, however, to be a prominent feature in the early portion of the Permian at least, but they probably declined in the later portion under the less favorable physical conditions then prevalent, supplemented by the attacks of the predaceous reptiles that had entered the arena. At any rate they were overshadowed in historical significance by the rise of the reptiles, without doubt their descendents. The Permian amphibians were of much the same types as before, with some advances in organization, and some reptilian tendencies.

The appearance of the primitive reptiles.—While the reptiles probably began to differentiate from their ancestral amphibians earlier than the Permian, the first demonstrable relics as yet found are from the lower strata of this period. Before its close, there had appeared a large and complex group of primitive reptilian forms very curiously related to one another, implying that they were yet in the early stages of their differentiation, and hence still retained various common inheritances from their ancestry, and implying also, probably, that they were affected by parallel evolution. There were, at the same time, signs of profound divergence. Two great branches seem already to have been defined in part; perhaps indeed they had never formed a common group, as reptiles, but had parted company while yet they were amphibians. The one (essentially the *Diapsida* of Osborn)[1] bore resemblance to the microsaurians and may have descended from them or from allied forms. In the earliest phases represented, they had already attained a decidedly reptilian structure of the rhynchocephalian type. They seem to have been the forerunners of the great hosts of lizards, crocodiles, dinosaurs, ichthyosaurs and flying saurians that constitute the most declaredly reptilian line; not that these were all necessarily descended from the Permian rhynchocephalians, but they form a great group marked by certain analogous features, implying either kinship in genesis, or kinship in evolution.

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[1] Amalitzky, Schrift d. Warschauer natur. Ges., 1895–1900.

The other group (*Synapsida*) bore skeletal resemblances to the highest labyrinthodonts, on the one side, and to the lowest mammals that appeared later (*Monotremes*), on the other, and hence may be regarded as constituting the mammalian strain of the ancestral reptiles. In their earliest known phases they were rather anomalous, and later they deployed into a remarkably complex order (thero-

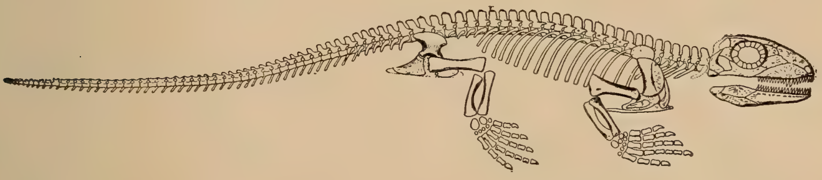

FIG. 299.—*Palæohatteria longicaudata*, a primitive diapsidan of the order *Protorosauria*, about ⅓ natural size. (Restoration by J. H. McGregor.)

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[1] Science, Vol. XVII, No. 434, 1903, pp. 275–276.

morphs or anomodonts) whose relationships and significances yet await resolution, for the greater part. Under the theromorph lineage are perhaps to be placed the turtles and plesiosaurs that appeared later. The more generalized or stegocephalian-like forms of the latter group have been given an ordinal rank as the *Pareiasauria* or *Cotylosauria* by some authors, who regard them as ancestral not only to the *Theromorpha*, but to the rhynchocephalian type of reptiles as well, thus giving expression to the view that the differentiation had occurred after the attainment of the reptilian form. Other groupings are made by other authors, implying that a final opinion is not yet universally reached.

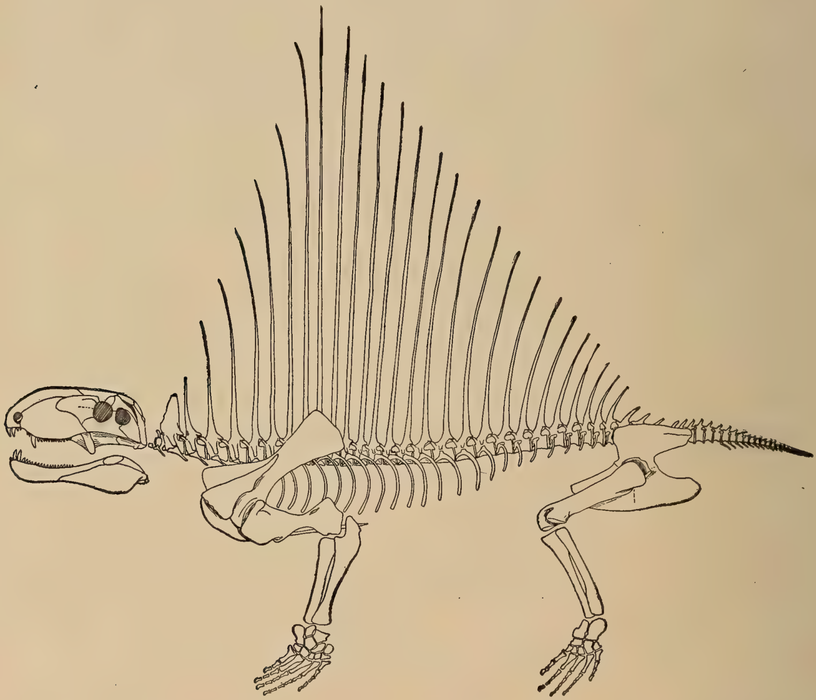

FIG. 300.—A fin-back lizard of the Permian of Texas (*Dimetrodon*). The skeletons found vary from three to ten feet in length. (Restored by Case.)

The more distinctively reptilian group (Diapsida).—The *Palæohatteria* of the Lower Permian of Saxony, a small, long-tailed, lizard-like reptile, is recognized at present as the pioneer of this branch (Fig. 299). It was typically rhynchocephalian, and is notable in that its line of descent is perpetuated to this day in the *Sphenodon* or *Hatteria* of New Zealand. With kindred genera it constitutes the suborder *Proterosauria*. Representatives have been found in England, Scotland, France, and Bohemia. They are not known in North America. An allied suborder (*Pelycosauria*) is predominantly American, and was represented by several genera (*Clepsydrops, Embolophorus, Dimetrodon, Naosaurus,* etc.) in Texas, Illinois,[1] and Kansas. There were also representatives in Europe. The skeletal features of one of the more typical genera, as worked out by Case, are shown in Fig. 300. A third suborder (*Proganosauria*) which some paleontologists believe to be rhyncocephalian in character, though by others referred to the *Sauropterygia,* had two genera (*Stereosternum* and *Mesosaurus*) of small, elongate, subaquatic reptiles (Fig. 301), from Brazil and South Africa.

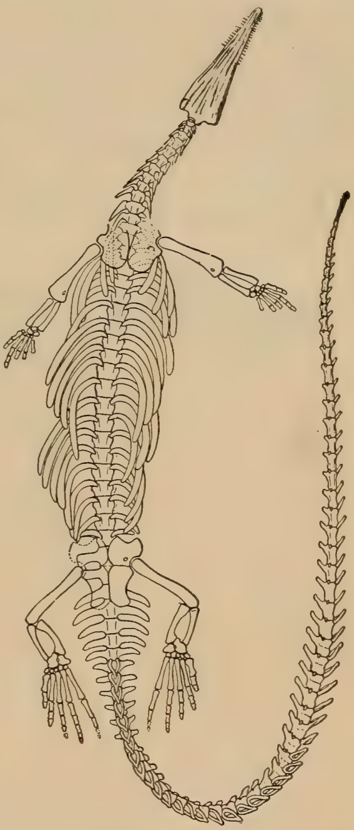

FIG. 301. — *Stereosternum tumidum,* from Brazil, about $\frac{1}{4}$ natural size, (Restoration by McGregor.)

The mammalian strain of the reptilian group (Synapsida). — At present the *Pareiasaurus* (Fig. 302) stands as the pioneer of this branch, and presents the nearest approach to the labyrinthodonts. The group seems to have diverged with great rapidity, for it developed markedly varied and strange forms by the close of the period. These diverse forms are grouped under the ordinal term *Anomodontia* by some authors, and by others under *Theromorpha,* in which case *Anomodontia* is restricted to a suborder (= *Dicynodontia*) under *Theromorpha.* The latter term refers to the mammalian features, the former to the peculiar dentition. The theromorphs deployed into four suborders, and became the dominant group among the earliest reptiles in each quarter of the globe where they have been discovered.[1] The most primitive of the suborders was the *Pareiasauria* or *Cotylosauria*, by many paleontologists now considered of ordinal rank, whose type family included the pioneer genus above illustrated. This family was abundantly represented in South Africa and in several parts of Europe, notably northern Russia, where Amalitzky has recently found many skeletons.[2] This family is not known in America, but two other pareiasaurian families are represented by several genera (*Otocœlus*, *Pariotichus*, *Isodectes*, *Pantylus*, *Hypopnous*, *Empedias*, *Diadectes*, *Chilonyx*, *Bolboden*). This distribution is very notable, considering the early stage of evolution of the reptiles.

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[1] The locality in Illinois appears to be simply an old river-bed eroded in the surface of the Coal Measures, and subsequently filled with alluvium, imbedding the reptilian remains.

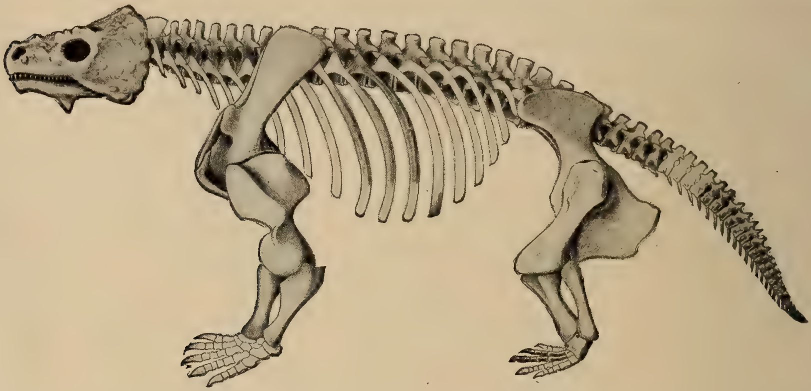

FIG. 302.—*Pareiasaurus serridens*, of Cape Colony, S. Africa, Karoo formation; × about $\frac{1}{25}$. (After Broom.)

The reptiles grouped under the suborder *Theriodontia* possess peculiar interest because of the mammalian aspect of their skulls, of their dentition, and of many features of their skeletons (Fig. 303). They were especially abundant in South Africa (Karoo beds [3]), but they have been found also in Bohemia, and notably in Russia (Amalitzky).

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[1] A. S. Woodward, Vert. Pal., p. 144.

[2] Compt. Rend., March, 1901.

[3] It is well to bear in mind that the Karoo beds, so wonderfully rich in significant vertebrate remains, are regarded as Permian in part and Triassic in part, and that a portion of their theromorphs belong to the latter. See also Broom, Geol. of Cape Colony, 1905, pp. 228–249.

The anomodonts, in the restricted sense (=dicynodonts), were highly specialized forms notable for their toothless jaws, or else jaws with single tusk-like teeth. The rest of the jaw was protected by a horny covering such as turtles have. Some features of their skulls also were curiously chelonian in aspect, and there may have been a genetic relation between the anomodonts and the turtles; but the evidence at present does not go beyond resemblances. The dicynodonts were probably herbivorous. The Karoo formation of South Africa has yielded them in greatest abundance, and they have also been found in India, Russia, and Scotland.

It is not certainly known that the fourth suborder of theromorphs, the *Placodontia,* were represented in the Permian, though their presence is probable. They were remarkable for their singularly modified dentition which has no parallel among reptiles. The teeth in front were conical, but the jaws elsewhere, and the palate, bore large molar-like grinding teeth. They are thought to have been allied to the ancestral turtles. These anomalous departures in dentition may have had some relation to the peculiar developments of the vegetation under the stress of the late Permian and early Triassic climatic conditions.

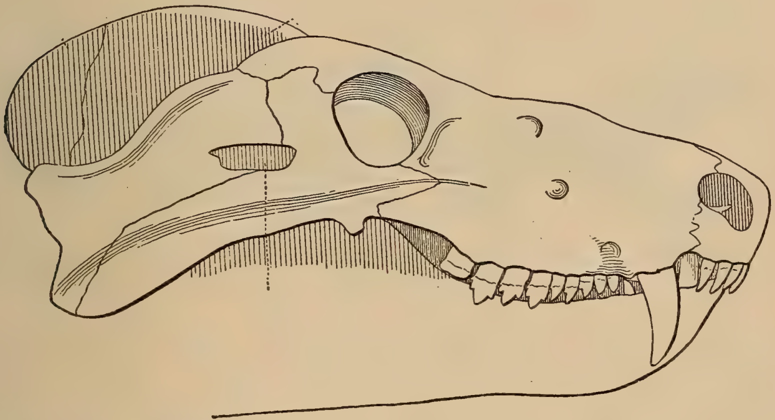

Fig. 303.—View of the right side of the skull of the theriodont *Cynognathus crateronotus*, from the Karoo formation, South Africa, showing the striking resemblance of the teeth and skull to a mammalian carnivore.

This rapid and diverse deployment of the early reptiles in a period of general life impoverishment is not a little remarkable, but as it was an evolution of air-breathers, the key to it may lie in a more oxygenated atmosphere, a point to which we shall return.

The scant record of other land forms.—The Permian record of the arthropods and of the terrestrial mollusks is very poor, and probably represents an impoverished state of these classes, but local exceptions will doubtless yet be discovered.

III. The Fresh-water Life.

The amphibians and some of the reptiles constituted, in a sense, a portion of the fresh-water as well as the land life. Besides these, fishes were abundant, locally at least. The beautiful little *Paleoniscus* (Fig. 304) seems to have had its climax here, and almost disappeared at the close of the period. Fishes of similar structure, but with deep, flat bodies, belonging to the *Platysomus* family, Fig. 305, were abundant. The modern aspect of these fishes will be noted. With these were some genera that had been prevalent before. Their associations show that they lived in fresh waters, but they may also have lived in the sea.

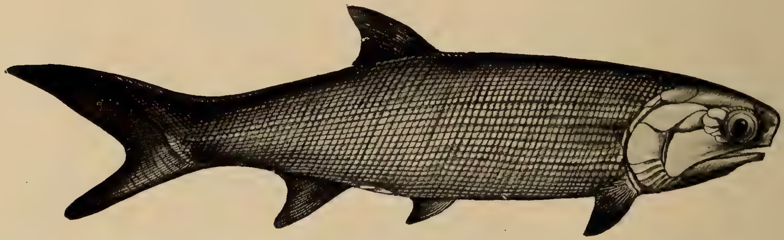

Fig. 304.—A Permian fish, *Paleoniscus macropomus*, from Thuringia. (Restoration by Traquair nearly one-half natural size.)

There were fresh-water mollusks, some of which resembled unios. The arthropod element was not well represented, though, so far as known, it shows but little change from the Carboniferous.

IV. The Marine Fauna.

The withdrawal of the epicontinental seas from considerable portions of the continents necessarily reduced the territory available for shallow-water life, and introduced a restrictional evolution. There was therefore at this time a coincidence between impoverishment on land, and restriction in sea, when normally the relations are reciprocal. In North America, the restricted marine area lay in the tracts just previously occupied by the expanded Carboniferous seas, and inherited its fauna from them. At first nearly all the species were the same as those of the preceding period, and hence a grave difficulty has always been experienced in drawing a dividing line between them. Prosser, who has carefully studied the Permian of the great plains, has recently listed the known species, and found only about seventy. This suggests a decadent fauna. Of these, about one half are pelecypods, which is doubtless a response to the increasing turbidity that attended the shallowing of the sea. Representative forms are shown in Fig. 306, *g–j*. Gastropods (Fig. 306, *k*), brachiopods, and cephalopods (Fig. 306, *a–f*) make up the larger part of the rest. Generally, the productids were the most characteristic forms, and the long-lived, cosmopolitan *Productus semireticulatus* frequented the seas in all quarters of the globe. It was the last flourishing stage of the productids, as well as of the orthids, the spirifers, and the athyrids, though the last two eked out a lingering existence till the Jurassic period.

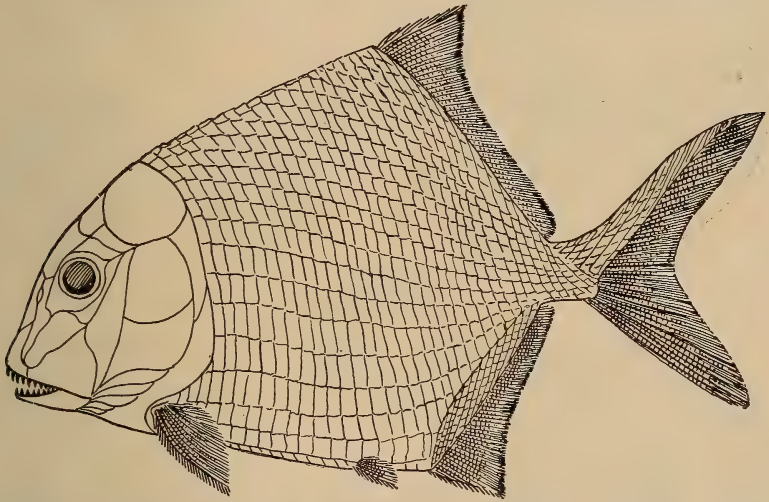

FIG. 305.—A Permian fish, *Platysomus gibbosus*, restoration by Traquair, about one-fourth natural size. Germany and England. (Woodward.)

The advent of the ammonites.—The increasing complexity of the sutures of the coiled cephalopods has been noted in previous periods. In the goniatites of the Middle Devonian, the sutures had become complexly lobed. A transition from the simply lobed goniatites to forms with more complicated sutures had taken place as far back as the Kinderhook epoch (see Fig. 235, *j*). In the latter part of the Permian period, forms with still more intricate sutures (Fig. 306, *c* and *e*), approaching those of the characteristic ammonites of the Mesozoic, became conspicuous. The genera *Medlicottia* (Fig. 306, *a*), *Waageno-*

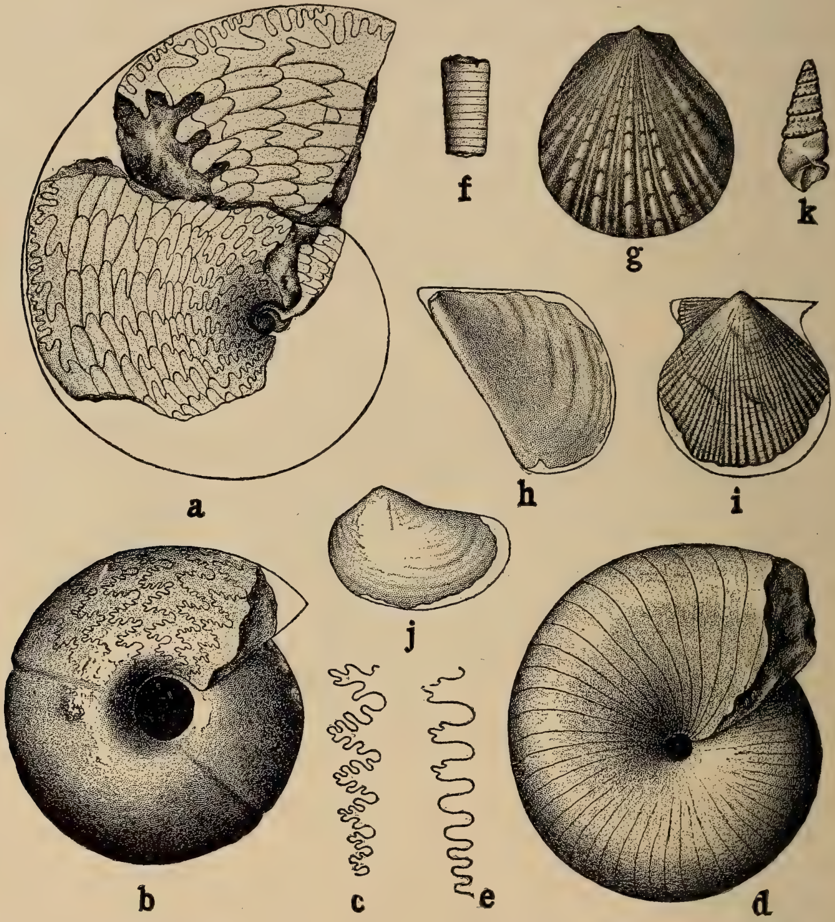

Fig. 306.—The Marine Permian Fauna: *Cephalopoda: a, Medlicottia copei* White; *b* and *c*, *Waagenoceras cumminsi* White; *d* and *e*, *Popanoceras walcotti* White; three forms of ammonoids with more complicated sutures than were present in earlier forms; *f*, *Orthoceras rushensis* McCh., one of the last of the orthoceratites. *Pelecypoda: g, Pseudomonotis hawni* (M. & W.); *h*, *Myalina permiana* (Swall.); *i*, *Aviculopecten occidentalis* (Shum.); *j*, *Sedgwickia topekaensis* (Shum.). *Gastropoda: Murchisonia* sp.

ceras (Fig. 306, *b* and *c*), and *Popanoceras* (Fig. 306, *d* and *e*) were representative types, occurring in America, Europe, and Asia. The older types of coiled cephalopods, the goniatites and nautiloids, mingled with these newcomers. Interestingly enough, there was also present the ancient straight form *Orthoceras* (Fig. 306, *f*), now reduced to primitive simplicity and diminutive size, lingering along in the last stages of its prolonged career, to finally disappear in the Trias. The contrast (compare Fig. 306, *f*, with *a*, *b*, and *d*) between the disappearing straight type, in its depauperate form, and the robust, youthful ammonites, about to become a ruling dynasty in its stead, is most marked. It was in this, as in not a few other cases, a Permian function to welcome the coming and speed the parting guest.

The retreatal tracts of the marine life.—As in previous transition epochs when epicontinental waters were largely withdrawn, the marine faunas found special refuge in certain embayments or border tracts which, in connection with the coastal belts, permitted them to re-form themselves, re-generate their species, and prepare for a succeeding invasion of the continental areas. On the American continent, the St. Lawrence embayment had done repeated duty in this line, but there is no specific evidence that it participated notably in the Permo-Triassic transition. The border of the Gulf of Mexico, the Mediterranean tract, notably in the region of Sicily and southeast Europe, and the Ganges-Indus tract of southern Asia, seem to have been special areas of refuge and regeneration. There are signs of another in northern Asia, and suggestions of still another in an unknown region from which the Triassic invasion of the *Tropitidæ* came. In these and doubtless other tracts, and on the continental borders generally, the shallow-water marine faunas passed from the Paleozoic to the Mesozoic phases. The restriction, compared with the expansional stage of the Mississippian period, was extremely severe, but the faunas emerged with new species born in adversity, ready for conquest when the re-advancing seas should give them an expanding realm.

The Problems of the Permian.

Between a marvelous deployment of glaciation, a strangely dispersed deposition of salt and gypsum, an extraordinary development of red beds, a decided change in terrestrial vegetation, a great depletion of marine life, a remarkable shifting of geographic outlines, and a pronounced stage of crustal folding, the events of the Permian period constitute a climacteric combination. Each of these phenomena brings its own unsolved questions, while their combination presents a plexus of problems of unparalleled difficulty. More than any other period since the Proterozoic, the Permian is the period of problems. With little doubt these marked phenomena were related to one another, and their elucidation is quite sure to be found in a common group of cooperative agencies. While it is too much to hope for a full elucidation at once, there is no occasion to blink the facts or evade the issues they raise.

Lest, however, we push our emphasis of these phenomena too far, let it be noted that none of the factors in this combination were wholly new to geological history. There had been glaciations almost as strange in early Cambrian or pre-Cambrian times (Norway, China, South Africa); there had been signs of aridity in the salt and gypsum deposits of Silurian and other early times; there had been prevalent red beds in the Old Red sandstone and in the Keweenawan; there had been marked restrictions of life at the close of the Ordovician and at other stages; there had been extensive geographic changes in earlier Paleozoic periods; and there had been foldings of surpassing intensity in Archean and Proterozoic times. The peculiarity of the Permian combination was its unusual complexity, the extraordinary intensity of the glaciation, and the aridity.

The chronological setting of the combination lends some advantages to its study. It lies in the midst of geologic history, with periods of great uniformity and remarkable polar geniality both before and after it. No appeal can be taken to a supposed final refrigeration of the earth, or to any declining stage or senile condition. It was an episode in the midst of a long history, with every probability that it was not without predecessor and successor, though these may not have been so marked.

A portion of the phenomena were direct expressions of deformation, others were seemingly close sequences of deformation, while still others may be only the more remote sequences of deformation in the form of changes of atmospheric and hydrospheric constitution. If the solution of these problems lies wholly in terrestrial causes, it seems at present most likely to be found in the immediate and ulterior consequences of deformation, as realized in physiographic changes, and in the constitution and working conditions of the hydrosphere and atmosphere. Without assuming that this is necessarily so, this line of inquiry, yet in its infancy, may be outlined.

I. The Deformation.

The deformation at the close of the Paleozoic appears to have been typical in that it involved an increase in the capacity of the oceanic basins and the withdrawal into them of most of the previous epicontinental waters, while at the same time the continents were rendered slightly more protuberant by being mildly arched or warped throughout the larger part of their areas, and, in certain limited tracts, accidented by sharp folding of the external shell. So far as present evidences go, the more pronounced arching and folding was felt chiefly on the borders of the continents adjacent to the north Atlantic, but this apparent limitation may be due to the imperfection of existing knowledge. Such limitation is not, however, out of harmony with what is known of other great deformative movements, for in these, as a rule, the more intense foldings seem to have been concentrated along restricted tracts.

Some of the dynamic conceptions involved in such a general deformation have been previously discussed (Chapter IX, Vol. I, and Chapter II, Vol. II). In special application here, it may be noted that during the Subcarboniferous and Carboniferous periods, in eastern America at least, a stage of approximate base-level seems to have been developed over some considerable portion of the territory, as shown by the configuration of the surface upon which the deposits of these periods encroached, and there is reason to believe that this condition was a rather general one. So far as can be judged from available evidence, this conception may be extended to all of the continents; indeed, this conception is almost necessarily involved in the wide transgression of the seas of these periods. This conception involves almost necessarily, as its essential prerequisite, the further conception of a protracted period of relative quiescence, for in such a period only could base-leveling be accomplished. It is presumed that during this period of quiescence, the energies that were to actuate the subsequent deformation were accumulating stresses preparatory to actual movement, for, in so far as loss of heat was one of the agencies, such loss must have been in progress; in so far as the internal transfer of heat was concerned, it also should have been in progress, and in so far as molecular changes were involved, they may be supposed also to have been going forward, or to have been acquiring the conditions prerequisite for action. It is, therefore, conceived that during the quiescent stage, stresses were progressively accumulating in the body of the earth, but that they only reached an intensity superior to the earth's resistance after a protracted period. When at length they surpassed all resistances, deformation went slowly forward until the stresses were, in the main, relieved, and the earth was thus prepared to relapse into another stage of relative quiescence. Considerations that have been previously presented make it appear probable that a large portion of the body of the earth was involved in the deformative movement, for, among other reasons, the portion of the crust which was folded had very feeble powers of resistance and cannot reasonably be supposed to have, of itself, accumulated stresses of the magnitude implied by the actual deformation. The phenomena seem to point to a high state of rigidity in the great body of the earth, and to the accumulation of very widely distributed stresses which were feeble at every point, and which only acquired effective strength by their ultimate union in a common movement.

The essence of the movement may be assumed, with much confidence, to have been a shrinkage of the earth, preferably a general and deep-seated shrinkage, rather than a purely superficial one. The shrinkage in the sectors beneath the ocean basins is presumed to have been slightly greater than that in the continental sectors, because of the superior specific gravity the sub-oceanic sectors are assumed to have acquired from their ancestral history, and because of their loading by the ocean, and by the sediments brought down from the land during the previous periods. At the same time, the removal of the sedimentary material from the land lightened the continental sectors and tended to disturb the balance between them and the oceanic sectors. The superior shrinkage of the oceanic sectors thus caused was probably attended by some crowding upon the weaker continental sectors between them, which appears to sufficiently account for the slightly increased protuberance of the continental platforms, together with the gentle warpings which they manifest, while the increase in the basin capacity resulting from the subsidence of the ocean bottoms accounts for the withdrawal of the epicontinental waters. The outer shell of the crust, being rigid and not under a load equal to its rigidity, appears to have accommodated itself to the shrinking interior by lateral shear and folding concentrated into tracts, instead of by a more distributive crumpling, or crushing. In this lateral thrust and folding is found the explanation of the post-Carboniferous mountains of eastern North America and western Europe, and such similar foldings as may perhaps have taken place in other regions at this time.

II. The Immediate Sequences of the Deformation.

Interference with circulation.—It is obvious that the withdrawal of the extensive sheets of water which had submerged the continents to the extent of perhaps 20,000,000 or 30,000,000 square miles, resulted in a serious restriction of the oceanic circulation, and correspondingly reduced the effects which such a general circulation had upon the climate of the times. These effects were probably profound. The surface temperature of the oceanic waters of the Mississippian and Carboniferous periods may, without any pretension to accuracy, be assumed to have been 25° C., or some such figure, as against the present 15° C. The submerged remnants of the continental platforms, while they must have interfered somewhat with the general oceanic circulation, probably did not so far interrupt it as to prevent the polar regions being warmed by a most effective water-heating system. No small factor in this, perhaps, was the deep circulation of the ocean, a matter of vital moment in all climatic studies.

In the discussion of the Pleistocene glaciation the possibility of the reversal of the deep-sea circulation by means of a change in the relative influence of the concentration of salinity by evaporation in the low latitudes on the one hand, and of increased density due to the low temperature in the high latitudes on the other, is entertained and its bearings discussed.

The deep oceanic circulation is now dominated by the *polar* temperatures, for it is the cold waters of the polar regions that, descending and flowing toward the equator, control the temperature of the deep sea. This is now low because of the low temperature of the polar regions; but if the circulation of the Subcarboniferous, and Carboniferous periods, whatever its nature, kept the polar regions at a mild temperature, the great body of the deep sea must have had temperatures correspondingly higher, and the water must have had so much the less depressing influence on the temperature when it rose to the surface. This must have contributed to the widespread warmth which the Subcarboniferous, and perhaps the Carboniferous, period enjoyed. The mildness of the polar climates in these and several other periods, before and since, is one of the most remarkable climatic features of geologic history. The crucial feature is the maintenance of a mild temperature throughout the long polar night. Almost the only approach to a satisfactory solution seems to lie in a warm oceanic circulation, blanketed by a heat-retaining atmosphere, in which vapor of water and carbon dioxide, abetted by a prevalent mantle of clouds generated by the warm ocean, conjoined their equalizing and conservative influences.

The transition from the Subcarboniferous to the Permian involved a change from an effective circulation of warm water to an interrupted circulation which limited the previous equalizing and conservative influences. This was one step toward a lowering of the polar temperatures, which perhaps ultimately reached the amount of 20° C. or more, and toward a lowering of the temperature of the great body of the ocean through the deep-sea circulation initiated and controlled by the polar temperatures. This was a step in the differentiation of regional temperatures, and this, as we shall proceed to note, was abetted by several other agencies arising from the same fundamental source, deformation.

Topographic sequences.—As already indicated, the deformation resulted directly in a pronounced change in the topography of the continents, in that it gave marked relief to the portions that were sharply folded, and a less declared but appreciable relief to the portions that were bowed upwards more gently. Both resulted in an increase of the general gradients of the surface, and hence in a rejuvenation of the streams. The increased area of the land obviously increased the number and the length of the trunk streams, and added to the volume of water that flowed through them, qualified, to be sure, by the aridity that followed. An inevitable result of these changes was a more rapid removal of the residual earth that had doubtless accumulated during the previous low-lying stages, and, following this removal, a dissection of the underlying formations and a lowering of the ground-water. An inevitable attendant of these sequences was an increased contact of the atmosphere with unleached rocks, combining at once the effects of the increased land area, the removal of the residual mantle, the dissection of the surface, and the lowering of the ground-water. The increase was probably several fold.

A complementary result of the increase of the land was obviously a reduction of the oceanic area and, particularly, a reduction of the shallow-water portion which had been the chief habitat of the limestone-forming life. From an area of perhaps 20,000,000 or 30,000,000 square miles in the early Carboniferous, the epicontinental seas were probably reduced to 10,000,000 or 15,000,000 square miles in the Permian, perhaps even to 5,000,000 square miles at the extreme stage of the Permian emergence. So great a reduction seriously curtailed the deposition of epicontinental organic beds, and markedly increased the deposition of clastic beds, and this was attended by other consequences now to be noted.

III. The More Remote Sequences of the Deformation.

Effects on the constitution of the atmosphere and hydrosphere.—It seems clear that if the contact of the atmosphere with rocks upon which it acts chemically were increased several fold, it would be robbed of its active constituents at a markedly increased rate. Chief among these active constituents is carbon dioxide, which unites with the silicates to form carbonates, and with the simple carbonates to form bicarbonates. The bicarbonate of lime in particular is thus formed, and, as the bicarbonate is much more soluble than the monocarbonate, its formation is the usual means of solution of limestone, and of its removal to the sea. Oxidation is next in order of activity. Starting with accelerated oxidation and carbonation, a series of complicated actions followed which are thought to have resulted in loss to the atmosphere and gain to the ocean. The present state of science does not permit these to be traced out with full confidence, but a sketch of some of the probable actions will serve to indicate the nature of the problem involved, and give some hint of its intricacy.

With little doubt it would be a serious error to start with the assumption that the atmosphere and ocean, when the deformation took place, had their present constitution. It is necessary, therefore, to consider at the outset what may have been the nature of the atmosphere and hydrosphere before the Permian deformation began to work changes in them. This leads us incidentally to consider certain radical questions that relate not only to these particular periods, but to similar periods when the land was low and limited, and great limestone deposition, and sometimes coal formation, took place. The two cases, great limestone deposition correlated with extended seas and low and limited lands, and great coal deposition, are not identical, though sometimes measurably combined. The Subcarboniferous period will be taken as the basis for considering the former, and the Carboniferous the latter.

The atmosphere and hydrosphere in the Mississippian and Carboniferous periods.—The facts that there was glaciation in low latitudes in the early Cambrian or pre-Cambrian, that there was pronounced aridity in the Silurian in regions where precipitation is now ample, that there had been active aërial life for some time previous, and that the respiratory organs of both plants and animals were strikingly similar in nature and proportions to those of recent times, combine to restrain us from assuming that the atmosphere, in any of the Paleozoic periods, was *radically* different from what it is now; but still certain moderate variations are not only compatible with these facts, and all other known phenomena, but seem to be required by the phenomena whose interpretation is here sought, as well as by theoretical considerations. The tracing out of these variations is apparently essential to the solution of the problems of these and similar periods.

The part played by the limestone formation.—During the Subcarboniferous period, a large deposit of limestone took place, the carbon dioxide of a part of which was undoubtedly derived from the atmosphere. While no accurate estimate of the amount of this limestone is now possible, it is certain that the total carbon dioxide in it is very many times greater than the carbon dioxide of the present atmosphere, and probably several times as great as the carbon dioxide of the atmosphere and the ocean combined. The calcium monocarbonate of the present ocean, by estimate, would make a stratum of limestone about ½ foot thick over the earth's surface, or about 4 feet over one half the present land area. The "loose" carbon dioxide united with this calcium monocarbonate to form bicarbonate, together with all the free carbon dioxide in the ocean, might, by liberal estimate, add 85% to this, if united with calcium to form limestone. The Subcarboniferous limestone mounts up in places to 2500 feet and more in thickness, and has a wide distribution on the land, and an unknown distribution beneath the sea. Without doubt we are accustomed to overestimate the mass of such formations, because we dwell upon their maximum, rather than their average or minimum thicknesses, and upon their known distribution in terms of our observational standards, rather than their proportions to the great unknown area of the globe; but yet from the data at hand, it seems inconsistent to assign the Subcarboniferous limestone a mass that is not much greater than the seven and a half feet for an area equal to half the present land, which is all that the present carbon dioxide of air and ocean could produce, if so converted. If we consider what a possible atmosphere and ocean richer in carbon dioxide might do, it seems idle to look to the atmosphere as even a possibly competent reservoir, consistently with the life that existed; for the carbon dioxide of the present atmosphere, if used up in making limestone, would form a layer of about one thirtieth of an inch thick only, over the globe. To form a layer one foot thick it would have to be increased 360 fold, which would surely imperil active, air-breathing life, unless it were different from similar present life.

The ocean under certain conditions has much greater competency to hold carbon dioxide, and, what is of prime importance, *to hold it in a condition harmless to animal life.* The carbonates of the present ocean, reckoned simply as monocarbonates, hold about 30 times the carbon dioxide of the atmosphere. To this is added a less amount in "loose" combination, to render them bicarbonates, and an additional quantity held by solution simply. Together, these may be roundly placed at 25 times that of the present atmosphere, giving in all 55 times the present content of the atmosphere. These are merely round figures, roughly approximate. Present data do not permit a close estimate of the "loose" and free carbon dioxide of the ocean.

The present ocean, however, is not saturated in calcium bicarbonate, for while the specific gravity of the sea ranges from 1.025 to 1.028, calcium carbonate is not precipitated appreciably until concentration by evaporation reaches 1.05, according to the careful investigations of Usiglio.[1] With the existing temperatures, it would be possible for the ocean to carry an additional amount of carbon dioxide in the form of bicarbonates,—precisely how much has not been experimentally determined. The higher temperature of the Subcarboniferous ocean would have been adverse; but it is probable that considerably more than 55 equivalents of the present atmospheric carbon dioxide might have been held by the ocean if it were as nearly saturated as was possible, and that without adversely affecting the animal life. It cannot of course be affirmed that this was the case; indeed the probabilities are against it for reasons that will soon appear. But, to make the most of this resource, let it be supposed that, at the opening of the Mississippian period, the ocean contained, by virtue of its carbonates, 60 to 80 equivalents of the present atmospheric carbon dioxide. Even this would fall far short of furnishing all the carbon dioxide locked up in the limestones of the period. It would, however, make a large contribution to the requisite amount, and thereby help appreciably to solve the problem, *provided it be assumed that the carbonates were removed from the ocean in the course of the period by consumption in limestone formation.*

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[1] Enc. Brit. Art. Sea Water, p. 229.

Could this have taken place? The conditions for the extraction of calcium carbonate by lime-secreting organisms were especially favorable. The map of the period (Fig. 228) indicates that, aside from the continental shelves, about 5,000,000 square miles of the continental area of North America were, by estimate, submerged, or more than half the present land area of North America. Great encroachments are known to have taken place on other continents, and a similar estimate of submergence of one half the present land area is probably in the neighborhood of the truth. If the submerged continental area for the globe be placed at 20,000,000 square miles, in addition to the 10,000,000 of the platform now submerged, it gives a vast tract of water peculiarly suited to be the habitat of lime-secreting life. When it is borne in mind that nearly the whole of the secretion of lime takes place in the upper few hundred feet of the sea, (1) through the agency of pelagic life whose habitat would be 10% greater than now, and (2) by epicontinental life whose habitat would be 200% greater than now, the potentiality of the geographic change may be realized. It is further to be noted that the warm temperature of the times not only favored an abundance of lime-secreting life, but favored the process of lime-secretion itself, for it is observed that the animals of the warm seas secrete more lime, on the average, than the same types in cold seas.

On the other hand, it is to be noted that the supply of carbonates from the land area was reduced in proportion as the sea was extended, and the land that remained unsubmerged was probably low, and had previously been much leached during the base-leveling processes. Hence the land waters penetrated the earth but feebly, from lack of head, and from hindrance by the deep mantle of residuary earth that presumably covered the low lands, and the carbonation and leaching of the lands was therefore relatively feeble. The seas were therefore much less rapidly supplied with calcium carbonate than in periods when the lands were broader and higher, and the penetration of the surface-waters deeper and more active. The period therefore presented conditions favorable for the extraction of lime from the ocean waters, and unfavorable for renewing the supply. Under these conditions, unless there be offsetting agencies not now recognized, it may be assumed that the carbonates of the sea were gradually reduced.

While the chemical relations involved are very complex and have not been much elucidated by direct experimentation as yet, and while the reactions are very difficult to anticipate theoretically, it seems permissible, in the present state of knowledge, to suppose that this process might go forward until the carbonates of the ocean were well nigh or quite exhausted. Even if completely exhausted, the calcium necessary for organic life could probably be supplied by the calcium sulphate, which is roundly ten times as abundant as the carbonate in the present ocean. Indeed, it has sometimes been urged that it is the calcium sulphate that is actually used by life, instead of the carbonate, but this does not appear to be sufficiently supported by experimental determinations. If calcium sulphate is converted by organisms into the calcium carbonate of their shells, skeletons, etc., the sulphuric acid set free probably unites with the bases of the carbonates of the water—except so far as converted into sulphides and deposited as such—and sets their carbonic acid free, so that the ultimate result of the reaction is much the same whether the organisms use calcium carbonate directly or calcium sulphate. This supposed depletion of the oceanic carbonates, even if it began with an ocean fully saturated by them and ended with complete exhaustion, would only *help* to solve the problem of the supply of carbon dioxide for the great limestone formations of the period, though the help would seem to be very important. But the depletion of the ocean content was probably a very radical feature in the atmospheric problem, to which this discussion is preliminary.

The rest of the solution of the problem of an adequate source for the carbon dioxide of the Subcarboniferous limestones is probably found in two other quarters. The limestone of the period was certainly not all original, in the sense of having been formed from the silicates of the crystalline rocks. A notable part of it was derived from the exposed portions of limestones previously formed. A comparison of the map of the period (Fig. 228) with the maps of previous periods (Figs. 95, 129, 174, 195, etc.), shows that not a little of the exposed land was formed of the older Paleozoic sediments, among which limestones were a notable element. Probably the lime in the previous sediments was not greater per unit area, on the average, than in the crystalline rocks, since the sediments were derived from the crystalline rocks. It was perhaps somewhat less, since there was some loss of lime to the ocean; but it was probably more readily removed. This removal involved the combination of a portion of the free carbon dioxide of the air with the limestone to form bicarbonate, which was thus dissolved and carried down to the sea. Thus a portion of the carbon dioxide was temporarily locked up, but when the lime was secreted by the sea organisms, this second equivalent of the carbon dioxide was set free, and was subject to diffusion into the atmosphere, where it was available for a repetition of the process. A comparatively limited amount of free carbon dioxide might thus serve, in time, as the carrier of a large amount of carbonate from the land to the sea. It is difficult to estimate the portion of the Subcarboniferous limestone which was thus derived from previous limestones, and the portion which was added by the original carbonation of the silicates of crystalline rocks, for the data are very inadequate.

The remaining source of carbon dioxide was found in volcanic emanations from the interior of the earth, and in the unknown supplies that came from cosmic sources.

All the foregoing sources combined may not improbably have been competent to furnish not only the carbon dioxide required for the formation of the limestone, but also for such other carbonate and carbonaceous deposits as took place. The feature of most note is the function assigned to the carbonates and carbon dioxide of the ocean, which, by being depleted during stages of great sea-transgression, meet the exceptional demands of the great limestone formations that characterize such periods, while at the same time, as the result of this, they leave the atmospheric-oceanic supply of carbon dioxide in a critical state of reduction.

The part played by coal-formation.—If the exceptional carbonic demands of the great Subcarboniferous limestone formation be met thus, in part, by depleting the ocean of its store of carbonates and carbon dioxide, the close of the period would have found this resource exhausted, and unavailable for meeting any exceptional demands during the following period; but it has been noted that there was an extensive withdrawal of the sea, in America at least, between the Subcarboniferous and Carboniferous periods. Much erosion and decomposition must have taken place to give the cherts and quartzose material of the Millstone grit and equivalent formations. So great thicknesses of chert as occur at many points imply the solution of much limestone, and this in turn implies large supplies of calcium carbonate carried to the ocean during the erosion interval; while the mere fact that the ocean was extensively withdrawn, and lime-secreting life restricted, implies a reduction of the drafts made upon its calcium carbonate for limestone formation. To make this reasoning altogether firm, the conditions in North America must, of course, have been representative of the world at large. In the aggregate, this is fairly warranted, but not conclusively shown, by present evidence. It may, however, be assumed tentatively that when the main deposits of coal and limestone began in the Carboniferous period, the ocean had become, in some measure, re-enriched in carbonates and loose carbon dioxide. During that period there were considerable limestone deposits, though these were not equal to those of the preceding period; and there were also large accumulations of coal and other carbonaceous materials which made heavy drafts on the supplies of carbon dioxide. Here again, the data for a numerical estimate are very imperfect. The productive coal fields of this age in North America are estimated to cover 265,000 square miles. North America embraces about one seventh of the continental surface of the globe, but has relatively more coal of this age than other continents. For a rough approximation, the whole may be put at two or three times that of North America. If the impure coals and other carbonaceous matter be included, an average thickness of 25 to 40 feet for the whole area may be assumed, without pretension to accuracy. The carbon dioxide of the present atmosphere, if reduced to pure coal, would give a layer about 1 foot thick over an area of 500,000 square miles, or about 8 inches thick over an area of 800,000 square miles. If there were no other demands than those of the coal deposits, these might apparently be met by drawing on the stores of carbon dioxide in the air and ocean, without supposing these supplies to have been very unusual. To meet the concurrent demand of limestone formation, it may be supposed that the oceanic supply of calcium carbonate was again greatly reduced. It is possible that the volcanic and cosmic contributions during the period were more than usual, but there is little clear evidence of it. Considerable volcanic activity is indicated by the igneous rock of the series in certain regions, but it is not extraordinary, and no very general prevalence is indicated. The more probable view appears to be that the carbonates and carbon dioxide of the ocean were again reduced to a low state, and that this was the condition when the deformative movements brought other powerful agencies into action.

The enrichment of the air in oxygen.—The extraction of carbon from carbon dioxide to form coal set free the associated two equivalents of oxygen, which contributed to the enrichment of the atmosphere in that vital element. While some oxidation was in progress during the period, the low elevation of the lands, and their limited area presented conditions less favorable than usual for oxidation. The presumption is therefore that oxygen accumulated, and that the Permian period inherited from the Carboniferous an atmosphere unusually rich in this vital constituent. This inference appears to be supported by the exceptional prevalence of highly oxygenated red deposits in the Permian and Triassic periods, and this is perhaps their sufficient explanation, when taken in connection with the climatic conditions of those periods.

The relations of equilibrium between the carbon dioxide of the air and that of the ocean.—To realize how it is possible for the atmosphere to vary in its content of carbon dioxide through only such moderate ranges as were compatible with active air-breathing life and yet be the medium through which the ocean yielded such large amounts of carbon dioxide as were demanded for the exceptional limestone and coal formations (over and above what the volcanos and cosmic sources can be presumed to have supplied during these times of exceptional demand), it is necessary to recognize that the carbon dioxide of the atmosphere is in a certain kind of equilibrium with the carbon dioxide of the ocean. This relation is peculiar and intricate, and the precise conditions and ratios of equilibrium are as yet but imperfectly determined. It involves a complex series of interactions between (1) anhydrous carbon dioxide (carbonic anhydride, CO_2), (2) carbonic acid (H_2CO_3), (3) calcium and other bicarbonates ($Ca(HCO_3)_2$, etc.), and (4) calcium and other monocarbonates $CaCO_3$, etc.). In the air there are carbonic anhydride and carbonic acid, and in the ocean, carbon dioxide, carbonic acid, calcium and other bicarbonates, and calcium and other monocarbonates. Some of these were merely mixtures whose distribution was controlled by diffusion and mechanical stirring. Others were dissolved and held by the force of solution, and others still were united chemically and held by chemical forces of different strengths. For the present purposes, it may suffice to note that a reduction of the carbon dioxide of the atmosphere calls forth carbon dioxide from the ocean to make up part of the loss, and bring the two into a new state of equilibrium.[1] The equalizing supply doubtless comes primarily from the free carbon dioxide or carbonic acid of the ocean, but the reduction which these thereby suffer causes the water to absorb some of the feebly combined carbon dioxide of the bicarbonates, while it is temporarily dissociated, thus reducing the bicarbonates to monocarbonates. In the case of calcium carbonate, this tends toward precipitation because of its slight solubility. In the opinion of some chemists, this process may go so far, if the atmospheric carbon dioxide is continually removed, as to call forth all the loose carbon dioxide of the bicarbonates of the ocean, and reduce them to monocarbonates, the calcium monocarbonate being precipitated, which involves the proposition that all the bicarbonates of the ocean are held there practically by the carbon dioxide of the air. Without accepting or rejecting this extreme proposition until experiments have gone farther and become more consistent, the more conservative observation that there is an interchange in the direction of equilibrium may be recognized as an important working factor.

The influence of the rate of diffusion.—But it is necessary to take careful note of the qualifying conditions and retarding agencies. The re-establishment of a state of equilibrium after it has been disturbed is dependent on diffusion and on mechanical mixture. If, for example, the air were robbed of one half its carbon dioxide, the ocean having, we will assume, 25 times as much, either in simple solution or in loose combination as the second equivalent of the bicarbonates, and remaining perfectly quiescent, the ocean would, by theory, ultimately give up enough carbon dioxide to make good about $\frac{25}{26}$ of the air's loss, and a new equilibrium would be instituted. To reduce the carbon dioxide of the air one half permanently, about one half of the great store in the ocean must be removed, as well as half of that in the air; hence the slowness of permanent changes in the carbon dioxide of the air. But this theoretical conclusion is qualified by the rates of diffusion of carbon dioxide in sea-water. The rate of this diffusion has not been experimentally determined, but supposing it to be as high as other rates of diffusion that have been determined, it would require millions of years for any notable percentage of the above restorative action to take place, and the completion, or even closely approximate completion, of the whole process would apparently require more than the lapse of known geologic history.[1] This, be it noted, is on the assumption of quiescent waters when diffusion acts alone.

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[1] The important conception of equilibrium was long since entertained by Schlœsing in its simple theoretical application to the existing status (Sur la constance de la proportion d'acide carbonique dans l'air, Comp. Rend., 1880, t. 90, p. 1410), and he regarded the ocean as a regulating reservoir, so to speak, restraining the fluctuations of the carbon dioxide of the air. This was a very valuable contribution, but in its secular application to geological problems, it must be recognized that all the factors are subject to change and, with them, *the basis of equilibrium itself*, and that the results are qualified by rates of diffusion, areas of contact, temperatures, and other elements. (See The influence of great epochs of limestone formation on the constitution of the atmosphere, Chamberlin, Jour. Geol., Vol. VI, pp. 609–621, 1898. A group of hypotheses bearing on climatic changes, Jour. Geol., Vol. V, pp. 653–683, idem. An attempt to frame a working hypothesis of the cause of glacial periods on an atmospheric basis, Jour. Geol., Vol. VII, pp. 545–584, 667–685, 757–787, 1899, idem; and also Tolman, The carbon dioxide of the ocean and its relation to the carbon dioxide of the atmosphere, Jour. Geol., Vol. VII, pp. 585–616, 1899.)

Krogh has recently made valuable contributions to Schlœsing's conception, but without adequate recognition of the qualifying and secular factors of the problem. (On the tension of carbonic acid in natural waters and especially in the sea, Vol. XXVI 1904, pp. 334–405, Meddelelser om Gronland, and The abnormal CO_2-percentage in the air in Greenland and the general relations between atmospheric and oceanic carbonic acid. Idem, pp. 409–436.)

The influence of agitation and circulation.—Agitation, combined with diffusion, accelerates the process, indeed, its efficiency is practically dependent on the surface agitation and on the circulation of the ocean. The agitation of the ocean is quite superficial, and the more conspicuous part of its circulation is also superficial. Now it is in this superficial, sunlit part that nearly all the plants of the ocean live, feeding upon carbon dioxide and setting oxygen free. This is partly, but not wholly offset, by the animal life in the same horizon, for observation shows that it is relatively low in carbon dioxide and high in oxygen. It is this inherently impoverished layer, especially affected by organic action, that is subject to agitation in contact with the air. This layer intervenes between the great bodies of the air and of the ocean that are but slightly affected by local organic action and between which the chief equilibrium exchange must take place, if it takes place at all. The diffusion which directly affects the body of the ocean is that between the superficial layer impoverished by plant action, and the great mass of waters below. If the matter were pursued into detail, it would be found that the state of carbonation of the superficial part of the ocean, and its interchange of carbon dioxide with the air above and the great body of the ocean below, are subject to much variation in different parts and different seasons; but upon this we cannot here enter.

That portion of the oceanic circulation which is most concerned in the carbonic equilibration of the air and ocean, is the deep circulation which now is initiated in the polar regions by reason of their low temperature. As this is a function of temperature, it brings us to the second qualification of the tendency to equilibrium.

The influence of temperature.—The coefficient of absorption of carbon dioxide in sea-water increases rapidly as the temperature is lowered, the rate being doubled for about 21° C., lowering[2] in the vicinity of 0° C. At present, the temperature of sea-water, in passing from the equatorial regions, where it rises from the depths, in the abysmal circulation, to the polar regions, where it descends, experiences a reduction of several degrees more than 21° C., and hence, if the air and ocean were in carbonic equilibrium at the equator, they would be far out of equilibrium in the polar regions. In such a case, in passing from the one to the other, the surface waters must be absorbing carbon dioxide, as long ago recognized by Dittmar and others. Relative to the average state of equilibrium for the whole contact surface, whatever that may be, the equatorial portion must be more highly charged, other things being equal, and the polar portion less highly charged. If the average state at the surface is near equilibrium, the equatorial portion is probably emitting carbon dioxide and the polar portion absorbing it. This is probably the actual condition now and perhaps has been generally in those geologic ages in which the climatic states were similar to those of the present. It may be accepted as a general proposition that, in the course of the abysmal circulation, essentially all oceanic waters pass through the absorbing stage in the polar regions and the emission stage in the equatorial regions, and that the adjustments of equilibrium for the great mass of the ocean are dependent on this slow circulation, whose period may equal a glacial epoch. In estimating it, the more active wind-actuated circulation of the surface must apparently be set aside, in the main, as having little to do with the abysmal circulation. It has recently been shown in the investigation of small lakes, whose depths rarely reach 200 feet, that the wind-driven circulation has little effect on the basal waters, but develops a surprisingly shallow superficial zone of its own. The waters below this are sometimes so far unaërated, or so charged with noxious gases, as to be offensive and inhospitable to life.[1] The temperatures of the deeper waters of lakes, however, show that there is a seasonal descent of cold waters analogous to the abysmal circulation of the ocean, but essentially independent of the eolian circulation. (For the hypothetical reversal of circulation, see pp. 432–446, Vol. III.) The discussion here will proceed on the supposition that the present deep-sea circulation was persistent.

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[1] This statement is based on a mathematical inspection by A. C. Lunn. For an analogous application of the rate of diffusion to lavas see Becker, Am. Jour. Sci. III, 1897, pp. 27–29.

[2] Krogh, loc. cit. pp. 363–365.

The influence of secular temperature changes.—If the polar temperatures in the mild stage previous to the Permian period averaged about 20° C., as the life seems to imply, the abysmal waters would become carbonated on the basis of polar absorption at 20° C. If, other conditions remaining the same, the polar temperature at the time of the Permian glaciation was reduced somewhat below the present temperature, the basis of equilibrium must have shifted to absorption at 0° C. to −4° C., or to an absorption ratio about double its previous one. In making the adjustment to the new basis of equilibrium, corresponding drafts on the atmospheric carbon dioxide are to be inferred. It follows from these considerations that at a time when the polar temperatures were being lowered, and *the basis of equilibrium* was being changed adversely to the atmospheric content of carbon dioxide, the latter was ill conditioned for meeting exceptional demands made upon it from other sources.

When this critical state, arising from the very conditions of equilibrium itself, is taken in connection with the depleted state of the oceanic carbon dioxide, arising from previous exceptional extraction to form coal and limestone, it will be apparent that the Permian deformation was liable to produce unusual effects.

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[1] E. A. Birge, Wis. Geol. and Nat. Hist. Surv.

With these conditioning influences and liabilities in mind, we may resume the sequences of the Permian deformation.

1. **Interruption of the water-heating system.**—The first effect, as already noted, must have been a serious interruption of the free polar circulation that had previously prevailed, and which has long been confidently regarded as one of the greatest of the agencies that maintained the previous mild temperature in those regions. In the Southern Hemisphere, the distribution of life furnishes special reasons for believing that the land was appreciably more extensive, and more completely connected, than it is at the present day, and geologists, quite without reference to any climatic effects, have postulated such connections. A migrating tract for land faunas and floras between India, Australia, South Africa, and South America seems to be requisite, and even if this were supplied in the most conservative way, it must have seriously interrupted the high-latitude circulation of that hemisphere. The constraint of the oceanic circulation in both hemispheres must have greatly reduced the temperature of the polar regions. This quite certainly led to greater differences of temperature between the air columns of different latitudes, and this must have intensified the vertical circulation of the atmosphere, and accelerated the loss of heat from the surface.

2. **Extension of continental climates.**—A second effect of the increase of the land areas was an increase of the continental elements of the climates, and a strengthening of the atmospheric circulation between land and sea. This further intensified the vertical circulation and accelerated the loss of surface heat. The mountains and other reliefs introduced by the deformation still further aided in checking horizontal circulation and intensifying vertical circulation.

3. **Reduction of humidity.**—A third effect was a reduction of the average moisture of the atmosphere. This is not only a firm theoretical deduction from the increase of the land area and the reduction of the water area, but is depositionally indicated by the remarkable prevalence of salt and gypsum deposits and of red beds. There is no question that the vapor of water plays a large part in the retention of the heat radiated from the earth, and so acts as a thermal blanket, and hence the reduction of this blanket led to less retention of the solar heat, and hence to a lower temperature. As this was truer of the land areas than of the oceanic, the climate must have been differentiated geographically into intensities of dryness and humidity, and of heat and cold. These must further have involved an increase of convective currents, and hence an additional loss of heat.

4. **Depletion of the heat-absorbing constituents of the atmosphere.**—A fourth effect is assigned to a change in the constitution of the atmosphere affecting especially its heat-absorbing constitutents. The reduction of moisture was a part of this change, but reference is here made to the more permanent constituents, particularly carbon dioxide. The increased area of the land, and its increased elevation, gave increased contact between the atmosphere and the rocks of the earth susceptible of carbonation and oxidation, as already indicated. As a result, the atmosphere lost carbon dioxide and oxygen at a more rapid rate than in the previous period. Oxygen plays some part in the thermal blanketing

of the earth, but any change it is likely to have undergone was probably not sufficiently large to make it needful to dwell upon it here. But if the carbon dioxide in the air and in the ocean was in the critical state of reduction we have inferred from previous losses, and was being absorbed by the ocean on account of the cooling experienced from the above changes of condition, the accelerated carbonation induced by the deformation may well have made serious inroads upon it. It is accordingly inferred that its quantity was reduced appreciably, and that the earth was thereby deprived of some large part of the thermal blanketing which it had previously effected.

The vicarious action of carbon dioxide.—Before considering the amount of this reduction, let it be noted that, in so far as it reduced the temperature, *it reduced the moisture in the atmosphere*, for this is immediately dependent upon temperature, and any agency which reduces the temperature reduces the moisture, and hence reduces the thermal effects due to moisture. Probably this secondary effect of a loss of carbon dioxide is greater than its primary effect. To realize this, it is important to recognize the fundamental difference between the relatively permanent constituents of the atmosphere, such as nitrogen and oxygen, and such an exceedingly dependent and fluctuating one as the vapor of water. No temperature effect arising from moisture seriously affects the amount of oxygen, nitrogen, or carbon dioxide in the air, while any reduction of these which involves reduction of temperature, effectually reduces the water-vapor. While a reduction of temperature does not immediately reduce the carbon dioxide, it leads indirectly to its absorption in the ocean, and so a reduction of either carbon dioxide or water-vapor reduces the other, and their mutual reaction intensifies their common temperature effect. Saturation being assumed, the theoretical amount of water varies with the temperature, but unequally. In the vicinity of 0° C., the amount of vapor varies roughly about 7% for every degree Centigrade, when computed from one degree to another, or, roundly, the vapor is about doubled or halved for every temperature change of 10° C.[1]

The amount of vapor in the air at −30° C., when completely saturated, about equals the normal amount of carbon dioxide in the air. The air is, however, rarely saturated with moisture. While, therefore, the amount of vapor in the air is, on the whole, much greater than the carbon dioxide, there are considerable high-latitude areas at the ground surface, in addition to the whole upper zone, in which the carbon dioxide exceeds the vapor of water.

The thermal functions of the atmospheric constituents.—Although not a little experimental work has been done on the competency of the atmospheric gases to absorb heat, it has not furnished an adequate basis for the satisfactory discussion of their relative serviceability in maintaining the temperature of the earth's surface. In part this has been due to the great difficulties of accurately determining the absorbent effects of the chief thermal rays, which have long wave-lengths ($.4\mu$ to 30μ) and are invisible. These long wave-lengths are almost the only ones that are radiated from the earth at its ordinary temperatures, and it is the retention of these upon which the surface temperature of the earth chiefly depends. It is only by the masterly work of Langley and others, that instrumental devices have been invented capable of exploring the lower end of the spectrum which is formed of these rays, and even these devices have not yet reached a sufficient degree of refinement to completely separate the individual effects of the gases. There is a further difficulty in the feebleness of the rays emanating from bodies at the temperature of the earth's surface. Higher temperatures, as that of boiling water, have therefore usually been employed in experiments; but as the proportion of short wave-lengths increases with the temperature, most of the experiments are not directly applicable to the problem in hand, and, besides, the results are not very consistent at best.[1] It is known that the same amount of moisture absorbs more radiation when near saturation than when much below it, which is perhaps due to a larger proportion of carbonic acid (H_2CO_3) in proportion to carbonic anhydride and water-vapor (CO_2+H_2O). The thermal efficiency of carbonic acid proper (H_2CO_3) has not been determined. For the present it is therefore necessary to accept rude approximations only.

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[1] For exact data, see Landolt and Börnstern's Physikalisch-Chemische Tabellen, or Evans' Physico-Chemical Tables.

Two modes of absorption of radiation are recognized, general and selective. When a molecule takes up those vibrations which it itself gives forth, when agitated, the absorption is selective. Gas composed of a single kind of molecules takes up the vibrations proper to it, as the string of a musical instrument takes up and reproduces the vibrations to which it is attuned. Other vibrations, for the greater part, pass through it without interference, but not wholly so. In partial and irregular ways, not fully understood, some parts of the vibrations of other lengths are absorbed. This incidental or irregular action constitutes general absorption. The nitrogen of the air does not absorb selectively much of the radiation of the sun or of the earth's surface, both of which pass through it with little modification, but not wholly without general absorption. Oxygen absorbs a larger number of known wave-lengths in the visible spectrum, but the amount of heat energy involved is not very large. Oxygen does not appear to absorb the long wave-lengths of the heat radiated from the earth to any notable extent. Carbon dioxide, on the other hand, absorbs certain bands of long wave-length rays whose energy is large. Arrhenius has lately determined experimentally the absorptive capacity of carbon dioxide for rays emitted by a body at 15° C., about the average temperature of the earth's surface, as follows:[2]

Amount of absorption	1%	2%	5%	10%	15%	20%	25%	30%
Amount of CO_2 traversed in cm. (at 15° C. and 760 mm. air pressure)	0.6	1.3	5	20.7	60	142	300	580

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[1] Paschen, Wied. Annalen, Vol. LIII, 1894; Angström, Ann. Phys. u. Chem. 3, 1900; Rubens and Aschkinass, Ann. Phys. u. Chem., 64, 1898; Arrhenius, Kosmische Physik, II, 1903.

[2] Kosmische Physik, II, p. 503. 1903.

These results are subject to some qualification because certain of the experimental conditions differed somewhat from those of the atmosphere, but they seem to be the nearest approach to natural conditions yet attained in experimentation. From the results, Arrhenius estimates that about 28% of the earth's radiation is absorbed (oblique transmission included), and that the carbon dioxide of the atmosphere influences the earth's temperature to the extent of 14.5° C. Ångström has estimated the absorption of carbon dioxide as at best only 16% of the earth's radiation.[1] From the percentage curves of Rubens and Aschkinass, applied to an energy curve determined by Ångström, we deduce about 8% absorption by carbon dioxide,[2] but the deduction is subject to several rather serious sources of probable error.

From Ångström's experiments, the following absorption values have been deduced [3] for water-vapor:

Amount of absorption	5%	10%	15%	20%	25%
Amount of vapor traversed (measured as water in cm.)	0.3	0.85	2.1	4.2	6.8

Owing to the differences of temperature, of the quantities used, of the degrees of compression, and of other conditions involved in the experiments, on the one hand, and to the lack of adequate data as to the average amount and distribution of moisture in the air, on the other, it is impracticable at present to deduce the relative values of the thermal absorption of the water-vapor and of the carbon dioxide of the present atmosphere, respectively, but it seems clear that the efficiency of the vapor is several times that of the dioxide.

The time of retention.—There is a defect in all the experimental work in that it does not show the secondary or retentional effects of added quantities of the gases. If a given quantity of gas absorbs 90% of all the radiation which that gas can absorb by selective action, the addition of a second quantity of equal amount could only selectively absorb, *at first hand*, its proper proportion of the 10% that had escaped previous absorption, but it would absorb *secondarily*, heat radiated from the previously absorbed 90%, and delay its escape, as well as radiate a portion of it back toward its source. It is not the simple absorption of heat that determines the climatic effect, but the time of its retention, or, in other words, the number of secondary absorptions and radiations. A given quantity of vibratory energy retained ten seconds within the basal stratum of the air by a series of re-absorptions and re-radiations, is as effective, climatically, as ten times the amount retained one second. While increase in the amount of a gas does not proportionately increase the percentage of primary absorption of the vibrations of its appropriate wave-lengths, it increases about proportionately the number of times these are absorbed and re-radiated before they finally escape.

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[1] Ann. Phys. u. Chem., 1900, p. 324.

[2] Ann. Phys. u. Chem., 1898, p. 598.

[3] Kosmische Physik, II, p. 505.

Primary independence in selective action.—It is important to note that *in selective action each gas absorbs its own wave-lengths, and these only.* No matter what its quantity or its relative competency, it cannot do the selective work of another gas. This is not experimentally demonstrable in the dark spectrum, from lack of sufficiently refined means of analysis, but in the visible spectrum the absorption lines of each substance differ from those of all other substances, so far as perfect determinations can be made, and there is no reasonable ground to doubt that this holds true in the dark spectrum also. Where bands appear to overlap, they are to be interpreted as intermingled groups of lines which are individually distinct. It is an error, therefore, to suppose, as some seem to have done, that any amount of water-vapor can replace, or interfere with, the absorption by carbon dioxide. Of the vibrations of various wave-lengths sent forth by the earth, a certain set are absorbed by the molecules of water, a certain other set by the molecules of carbon dioxide, some few others by the other gases, and the rest escape, except as caught by dust, clouds, general absorption, etc. This relates to primary action, and to a certain portion of the secondary action.

After a molecule of carbon dioxide has absorbed its appropriate radiation, and increased its vibratory energy correspondingly, it radiates wave-lengths of its own kind, which can be taken up by other molecules of carbon dioxide, but not by the molecules of other gases. The number of re-absorptions and re-radiations of such wave-lengths is dependent upon the number of dioxide molecules that lie in the paths of such re-radiations, which are in all directions, some being, of course, back toward the earth, or laterally, where they will be re-absorbed in adjacent parts of the atmosphere. The same is true, of course, of all the other molecules relative to vibrations of their own wave-lengths. Thus there is measurably perpetuated independence of action.

Thermal transference by molecular contact.—While, however, the preceding action is in progress, each molecule is colliding with its neighbor molecules many million times per second, and communicates some of its heat energy by such contact. The molecules thus heated radiate wave-lengths of their own order, and *these* may be absorbed by molecules of the same kind. Thus vibrations may be transformed so as to be absorbed by all the constituents of the air in succession, and their retention within the air be greatly prolonged, because of the great mass of some of these constituents.

The critical point is obviously the first absorption that starts the transfer by impact. If there is no constituent to take up the vibration from the ether, it escapes, but if it is once taken up by a molecule, it may be transferred a multitude of times before it escapes.

Just what is the measure of the efficiency of carbon dioxide in contributing to the temperature of the earth is not yet determined, and so the influences of changes in its amount on the climate are as yet undeterminable, but as one of the factors in the complex of agencies, it seems to require a place in our working hypotheses.

Total thermal efficiency of the atmosphere.—It seems worth while in this connection to try to estimate the total agency of the atmosphere in preserving the temperature of the globe. The earth and moon are at practically the same mean distance from the sun, and would doubtless have practically the same temperature if the earth had no atmosphere or ocean. (The ocean is theoretically a derivative from the atmosphere.) If the present mean temperature of the earth's surface be taken at 15° C., the absolute temperature is −288° C. As the result of a recent elaborate study, Very estimates the temperature of the moon at its midday to be 97° C.[1] Several other astronomers have thought that the moon's midday temperature did not rise much above the freezing-point. The range of competent opinions may then be limited by the boiling- and freezing-points, 373° and 273° absolute. It is agreed by all that the lowest night temperature cannot be far from absolute zero. Allowing this, however, to be 55° absolute, the average temperature of the moon on the higher estimate is 214° and, on the lower, 164° absolute. The difference between these, respectively, and the mean temperature of the earth, 288°, is 74° and 124°, of which the mean is 99°. While there is a rather large element of uncertainty in the estimates of the moon's temperature, their mean gives countenance to the belief that the efficiency of the earth's atmosphere, as a thermal blanket, may be in the neighborhood of 100° C.

If the mean temperature of the earth in the Carboniferous period be placed at 25° C., it will doubtless be about high enough, for that is a tropical temperature, and if the mean temperature of the glacial stages of the Permian be placed at 10° C., this will perhaps be low enough. The range between these, 15° C., would, on the basis above deduced, make the change from the one to the other only 15% of the total efficiency of the atmosphere. When allowance is made for the effects of increased vertical circulation, it does not seem that it is taxing the assigned changes in the water-vapor and carbon dioxide too severely to make them responsible for the remaining portion of the 15% of the whole thermal competency of the atmosphere.

IV. The Localization of the Glaciation.

The remarkable distribution of the Permian glaciation is the most puzzling feature of the whole problem. The localization of the recent Pleistocene glaciation was also peculiar, as will be seen, but still it was measurably circumpolar, as we should expect any general glaciation to be. Among the explanations offered for this later puzzle is one which connects it with the areas of *permanent low atmospheric pressure* in the North Atlantic and North Pacific regions, in which the present glaciations of Greenland and Alaska are located, and to which they apparently owe their exceptional development.

Tentative conception of the "fixed lows" and their relations to glaciation.—The cause of the prevailing low pressure and permanent cyclonic character of these areas is yet to be demonstrated, but one of the conceptions of their dynamics that seems to be warranted at present, seems also to be helpful in explaining peculiarly localized glaciation. In this conception, mechanical and vaporous energy are assigned a controlling value in determining the special configuration of the air movements, while thermal energy is placed in the background in a double sense. It is, of course, recognized that, at bottom, the chief agency in atmospheric circulation is unequal heating. Unequal distribution of moisture is also an original agency, since the superior kinetic energy of vapor, relative to its weight, renders the air column of which it forms a part lighter than if formed of dry air, other things being equal. This amounts to an appreciable agency. While the amount of its effect is dependent on the absolute amount of vapor present, its operative efficiency is dependent on the difference in its abundance in the different parts of the atmospheric province, precisely as in the case of heat. Starting from one or the other of these original sources, or from a combination of the two, circulation is inaugurated; but, when once under way, many secondary factors of a mechanical, rather than thermal or vaporous nature, are developed, and these appear to greatly influence the special configuration which the air movements and even air pressures actually assume. Some of these mechanical factors are closely derivative from the original thermal or vaporous energies, as the exceptional violence of squalls, tornadoes, etc., while some spring from the modifying effects of independent agencies, as the rotation of the earth, the configuration of the surface, the distribution of land and water, the ocean currents, etc.

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[1] Probable range of the temperature of the moon, Astrophys. Jour., VIII, 1898, p. 265. See also the temperature of the moon, S. P. Langley, assisted by F. W. Very, Nat. Acad. Sci., I.

Now, it is conceived that in a region where the agencies last named are specially influential, and the influence of differential temperature is not particularly strong, the mechanical factor and the vapor together may be dominant, and as they are fixed geographically, the cyclonic area also becomes fixed, instead of moving with the atmosphere, as do the more familiar cyclones. It is not intended, however, to imply that even these are not measurably dependent on derived mechanical energies. It is further conceived that in these fixed cyclonic "lows," the moist air of the great central tract is mechanically forced to rise *at a relatively low temperature* and the precipitation is hence favorable to glacial accumulation. In a more purely thermal cyclone, the relatively high degree of heat involved in *immediately* actuating the cyclonic movement is present to antagonize glacial accumulation. This conception is extended to the moving cyclones within the permanent cyclonic area, and perhaps even beyond. It is to be understood that this is not established meteorological doctrine. These are problems, like the rest of this complex of puzzles, yet awaiting final elucidation. The special point of application here lies (1) in the fact that this conception provides for precipitation with a minimum of heat by assigning mechanical energy and vaporous levity as the dominant actuating agencies, and (2) in that it gives a fixed location to the low-temperature precipitation that follows.

Probable geographic features of the glacial stage. — If the land extensions and connections in the Southern Hemisphere in the Permian period be made as slight as biological data permit, they would probably at least consist of a connection from India, *via* Australia and the old submerged land, to New Zealand, and thence to Antarctica, and through this to South America. Other and more northerly connections between India and South Africa, and between the latter and South America, have usually been postulated. In the minimum case, the oceanic circulation must have been very different from the present, for the warm equatorial currents from the Pacific that now flow through the East Indian straits into the Indian Ocean must have been turned back into the Pacific, concentrating its heat there. At the same time, two thirds of the cold waters flowing along the borders of Antarctica, which now largely pass south of New Zealand into the Southern Pacific, must have been arrested by the postulated New Zealand-Antarctican isthmus and turned northward into the Indian Ocean. The joint result was a concentration of warm water in the Pacific, and of cold water in the Indian Ocean.

A broad Arctic tongue of sea is thought to have occupied eastern Russia and western Turkestan about this time. It appears to have had an open polar mouth, but its ulterior connections in the Arctic regions are unknown. So, too, its connections toward the south and east are uncertain at the precise time of the glaciation. It is not, however, beyond permissible hypothesis to suppose that this Arctic embayment may have been occupied by a returning Arctic current of the Labrador type. If so, this tended to extend the Arctic low temperature equatorward in about the same longitude as the Antarctic movement.

The hypothetical development of localized glacial conditions.—The postulated effect of these configurations was the concentration of large portions of the polar currents in the longitude of the glacial areas, resulting in the intensification of the atmospheric gradients on that side of the sphere, and leading to a peculiar asymmetry in the atmospheric circulation. Hypothetically, this called into play, in an unusual degree, the derivative mechanical factors in the circulation, and led to the development of fixed cyclonic areas in exceptionally low latitudes. The cold polar currents are assumed to have furnished to the centers of the fixed "lows," cool moist air, which, forced to rise rather by mechanical movement and aqueous kinetic action than by high temperature, gave *persistent precipitation at sufficiently low temperatures to promote glaciation.* Persistent clouds and fogs, habitual in such situations, are presumed to have shielded the glacial surface by their high reflecting powers, and to have become important auxiliary agencies.

Alternative views. — The special problem of Permian glaciation has not developed such voluminous discussion as has that of the Pleistocene period, largely because its verity has only recently been established, and because the majority of glacial students are not personally familiar with its phenomena. A change of the earth's poles has naturally been suggested, since a shifting of the south pole to the center of the Indian Ocean would relieve the problem of its most refractory element, the location of the glacial areas on the borders of the tropical zone. Such a shifting, even if we ignore the extremely serious dynamical difficulties involved, does little more than mitigate the problem of localization, for if the pole were placed equidistant from the three glacial centers in

India, Australia, and South Africa, it would be farther away from any one of them than is any present center of continental glaciation from the present poles. In most of the ancient periods, the polar regions do not seem to have been affected by glaciation, but rather to have been frequented by ferns, corals, figs, and magnolias. A general climatic stage verging toward glaciation and furnishing an appropiate climatic environment for a regional concentration of frozen precipitation, is prerequisite, and this is the primary problem.

Local elevation has been postulated, but the stratigraphic and other geologic evidences do not seem to support it. Marine beds are interstratified in the glacial series without evidences of extraordinary elevation and intensified erosion between their respective depositions. A case has been cited in which a bivalve was found standing on edge, as in life, in clay among glacial bowlders. Other evidences of iceberg deposition have been adduced, implying that the glaciers reached the sea.

The Crollian hypothesis[1] assigns this as well as other glaciations to a temporary increase in the ellipticity of the earth's orbit. If the fundamental conception is valid, ellipticity might be a cooperating agency, but, as already remarked, the general conditions that render any areal glaciation on lowlands possible would seem to be a prerequisite to its effective action. The hypothesis is virtually reducible to a change in the distribution of heat between summer and winter, the sum total of the heat remaining the same. In those periods in which the polar night was not fatal to ferns, figs, and magnolias, the elliptical variation could scarcely be effective.

Among the purely astronomical hypotheses, the variability of the sun's heat, which is supported by the recent observations of Langley[2] and Abbot, is the most substantial. Obviously, however, short-period variations in heat emission are inapplicable, as the glacial epochs can scarcely have been less in length than some few tens of thousands of years each; and the problem of localization, that thorn in the flesh of all hypotheses, is left untouched.

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[1] Climate and Time.

[2] The solar constant and related problems. Astrophys. Jour. 1903, pp. 89–99.

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